NTNU – Trondheim
Norwegian University of
Science and Technology

The identification of quick clay layers from various sounding methods

Tesfaye Kerlos Tilahun

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Supervisor: Arnfinn Emdal, BAT
Co-supervisor: Vikas Thakur, Statens vegvesen

Norwegian University of Science and Technology
Department of Civil and Transport Engineering

Norwegian University of Science and Technology

Department of Civil & Transport Engineering

Geotechnical Division

Master thesis

The identification of quick clay layers from various sounding methods

By

Tesfaye Kerlos Tilahun

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Name: Tesfaye Kerlos Tilahun				
Main Supervisor: Arnfinn Emdal (NTNU)				
External Supervisors: Rof Sandven (Multiconsult) Vikas Thakur (Norwegian Road Administration)				

Abstract :

Quick clay has been involved in most serious, large clay slides in Norway, Sweden and Canada (Lundstrom K., Larsson, and Dahlin, 2009).

The main purpose of this thesis work is to analyses the raw data from different geotechnical soundings. The correlation between the tip resistance and the slope angle of the resistance versus depth curve that can be used to locate and map the extent of quick clay layer will be the main focus.

The approach of this analysis is devised from a review of the literature; and case studies are used to investigate what has been done so far and the methodologies used in the case sites. Raw data from seven site investigations are collected and used for the analysis. The interpretation of the plots for quick clay has been compared with remolded shear strength which is determined using fall-cone tests and other relevant of laboratory investigations. To some extent, the electrical resistivity data was also used. Although the most reliable evaluation of the variation in sensitivity was obtained by the CPTu with additional measurement of total penetration force, this investigation suggests that any sounding method that uses a constant rate of advance into the ground may be used for quick clay mapping. For a long time, the predominant method for detection of quick clay has been to take undisturbed samples and to perform fall-cone tests on the clay in its undisturbed and remolded state.

The CPTu, rotary and total sounding testing data not only provide valuable information on the location of the quick clay layer. It is also useful in driving correlations with the engineering properties of soil for the purposes of analysis ,design of foundations and mappings of areas where quick clay is a problem. In a view to establish a region-specific correlation between penetration resistance and soil properties, (CPTu), borings, and other in situ tests were carried out at different sites in Norway. CPTu and rotary or total sounding data were plotted, interpreted and used for the identification of the quick clay layer. These results are further validated with the soil classification determined from the field samples and basic soil test results from laboratory.

The plot interpretation and the overall approach might help for a better understanding on how the plots of the different sounding results against depth and how it is more related to the main purpose of the identification methods used so far.

The research results are limited within the context of the available data collected from different sites.

Key words:

-Quick clay

-CPTu sounding

-Total sounding

-Rotary sounding

-Resistivity

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(Signature)

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The identification of quick clay layers from various sounding methods

Background

Quick clays involve considerable risks, for example in connection with stability problems, where small impact may change into large landslides involving the entire quick clay formation. The sliding masses obtain a consistency of heavy liquids, which can flow over large distances and cause extensive damage to anything in their path. The existence of quick clay may also cause part of the structure to break down due to its weak property, as it is remolded by the construction activities which leads to extreme reduction of the shear strength. This will increase the risk of both settlements and stability problems. There are no generally adopted uniform methods of quick clay identification method which can help for the reliable mapping purpose. Rather, in most cases, the existence of quick clay is observed in the results of the ordinary geotechnical investigation methods, mainly various sounding methods and laboratory tests on retrieved samples.

For different projects, the routine laboratory investigations which include the identification of quick clay has been done using the falling-cone test on the extracted clay, both on an undisturbed sample and then on the remolded sample. Therefore, the extent of the quick clay formation is estimated from the existing results of the investigation and various arbitrary considerations.

This master thesis is a part of the national program called Natural Hazards, Infrastructure, Floods and Slides (NIFS). NIFS is a joint project between the Norwegian Water Resources and Energy Directorate (NVE), Rail (JBV) and the Norwegian Public Roads Administration (NPRA).

Project Tasks

This thesis focuses on the identification of quick clay or in more broad perspective the highly sensitive clay using the data from various sounding methods that includes rotary sounding, total sounding and CPTu.

By the end of this work, the following out comes are expected:

- Literature review on the identification process and methodologies used so far
- Interpret the plots for the identification of the quick clay layer and evaluate the correlation between the slope of the penetration force and the presence of quick clay
- Come up with the most reliable approach, after analyzing the available data, which can be used for a better mapping purpose

A study of previous works and identification methods compared to the current approaches which is to get some empirical correlations between the tip resistance and the remolded shear strength of clay which leads to the more dependable method using the available data taken from field and laboratory tests. A discussion of the similarities in results as well as the discrepancies is of interest.

Arnfinn Emdal
NTNU

Vikas Thakur
Norwegian Public Roads Administration

Rolf Sandven
Multiconsult

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List of symbols and abbreviations

q_c	Uncorrected cone resistance
A_s	Friction sleeve surface area
CPTu	Cone penetration test with pore pressure measurement
OCR	Over consolidation ratio
f_s	Sleeve friction uncorrected
σ'_p	Maximum past effective consolidation stress
a	Unequal area ratio
σ'_{vo}	Effective overburden stress,
q_t	Corrected cone resistance
σ_{vo}	Total overburden stress
f_t	Corrected sleeve friction
s_u	Undrained shear strength
u_3	Excess pore pressure measured at upper end of the friction of the sleeve
Δ_u	Excess pore pressure
u_2	Excess pore pressure measured at lower end of the friction sleeve
A_{sb}	Cross sectional area for the top sleeve
u_1	Pore water pressure on the cone
A_{st}	Cross sectional area for the bottom sleeve
u_2	Pore water pressure behind the cone
f_t	Corrected sleeve friction
u_0	Hydrostatic pore water pressure
CPT	Cone penetration test
R_f	Friction ratio
N_m	Cone resistance number
N_{ke},	Cone factors based on effective cone resistance
N_{kt},	Cone factors based on corrected cone resistance
Q_t	Normalized cone resistance
B_q	Pore pressure ratio

A_s Friction sleeve surface area

σ_{vo} Total overburden stress

σ'_{vo} Effective overburden stress

s_u Undrained shear strength

Δu Excess pore pressure

u_1 Pore water pressure on the cone

u_2 Pore water pressure behind the cone

u_0 Hydrostatic pore water pressure

w water content

w_l Liquid limit

w_p plastic limit

I_p Plasticity index

I_l Liquidity index

BH Bore hole

1. Introduction

Almost all landslides in clays in Norway, Sweden and Canada with significant consequences can be designated as quick (or highly sensitive) clay slides (Lundstrom K., Larsson, and Dahlin, 2009). Examples of quick clay landslides in Scandinavia with serious consequences over the last 60 years include the Rissa, 1978, and Trögstad, 1967 slides in Norway, and the Surte, 1950, Göta, 1957, and Tuve, 1977 slides in Sweden. The location, time of occurrence, and size of quick clay slides are difficult to predict, which is unfortunate as large slides may cause great devastation. The extent of such slides is governed largely by the sensitivity of the clay to disturbance(Lundstrom K., Larsson, and Dahlin, 2009). As quick clay is such an important factor in the determination of stability, it is critically important to know if quick clay is present, and if so, to what extent. The designation “quick clay” refers to clay whose structure collapses completely upon remolding due to disturbance, which causes an almost total loss of shear strength (Lundstrom K., Larsson, and Dahlin, 2009).

In Norway we use the term brittle clay, which include the quick clay (C_r<0,5 kPa) and sensitive clay (S_t>15, C_r < 2,0 kPa). These criteria’s are considered together when evaluating slide risk and consequences, at least formally.

The most common method used to detect quick clay is to take undisturbed samples and to perform fall-cone tests on the clay in both its undisturbed and remolded states. However, mapping of quick clay formations in this way requires extensive sampling. For economic reasons, the method is therefore not usually applicable for a detailed mapping of the extent of a quick clay location; with only at a few locations in selected investigated sections.

In Norway, there is one common used method for establishing the presence of quick or highly sensitive clays in connection with slope stability assessments. This involves rotary pressure soundings (described below) at uniform specified distances along the slope (NGI, 1970). The results of the rotary pressure soundings are scrutinized according to guidelines presented by (Rygg N., 1978), and any parts of the curves that are smooth and almost vertical are designated as likely being very sensitive clay. The actual sensitivity is then checked by field vane tests or laboratory testing on obtained samples, if required.

The aim of the investigation described here was to study quick clay identification techniques and finally to come up with the correlation between the slope of the resistance with depth for quick clay mapping and to evaluate their usefulness and reliability.

1.1 Formation of quick clay

At the height of the past glaciation (about 10,000 years ago), the land was 'pushed' down by the weight of the ice. All of the ground-up rock was deposited in the surrounding ocean, which had penetrated significantly inland. The loose deposition of the silt and clay particles in the marine environment, allowed an unusual flakes to take place. Essentially, this formed a strongly bonded soil skeleton, which was 'glued' by highly mobile sea-salt ions (Rankka and others, 2004). At this point, there was only the formation of very strong marine clay, which is found all over the world and highly stable, but with its own unique geotechnical problems. When the glaciers retreated, the land mass rose (post-glacial rebound), the clay was exposed, and formed the soil mass for new vegetation. The rain water in these northern countries was quite aggressive to these clays, perhaps because it was softer (containing less calcium), or the higher silt content allowed more rainwater and snowmelt to penetrate. The final result was that the ionic 'glue' of the clay was weakened, to give a weak, loose soil skeleton, enclosing significant amounts of water (high sensitivity with high moisture content).

Quick clay deposits are rarely located directly at the ground surface, but are typically covered by a normal layer of topsoil. While this topsoil can absorb most normal stresses, such as normal rainfall or modest soil movements, a shock that exceeds the capacity of the topsoil layer such as a larger earthquake, or an abnormal rainfall which leaves the topsoil fully saturated so that additional water has nowhere to go except into the clay can disturb the clay and initiate the process of liquefaction.

1.2 Motivation of the study

Different approaches have been made for the identification of the quick clay. However, still there are some uncertainties on the outcome of the identification as some results are not giving the expected outcomes. Some data found from the investigation method show that there is a quick clay layer from the nature of the curve that usually used for the identification purpose, but when the actual sample is extracted and tested, it give totally a non-quick clay property. Therefore, there should be some misunderstanding of the interpretation which leads to wrong judgment.
The current study was designed in such a way that it would supplement to the ongoing research by giving some important insights related to the reliable identification of the quick clay layer from the correlation of sounding technics and laboratory test results.

1.3 Objective of the study

The objective of this study is to contribute some efforts for the researches which has been done so far and to come up to the more reliable identification of the quick clay layer that finally contributes to the mapping of this problematic soil layer at once.

1.4 Study methodology

Regarding the identification of the quick clay layer, different methodologies and techniques has been used. In this study, available data from all geotechnical sounding methods and related laboratory results will be used. All the common criteria's previously used to decide if the clay is quick clay or not will be tried to correlate and come up to the same implication that the soil is really a quick clay or not.

1.5 Scope of the study

The present study has aimed at obtaining sufficient data to evaluate different sounding methods and to come up to a more reliable identification which finally helps for the better and more reliable identification of quick clay layers that helps for the mapping of the area for future use. Even though many site investigations are made all over Norway, for this study, data are taken from different sites which believe to be helpful for the thesis. Åby site, southern Norway, Kaldvelladalen and Fallan Mid-Norway, Byneset west of Trondheim, Tiller southern Trondheim E6-Harran and E39- road project are the sites selected for this study.

1.6 Organization of the thesis

The organizations of the remaining chapters of this thesis are briefed below.

Chapter 2: Reviews limited background literature and highlight some important researches in the identification of quick clay which were found to be more relevant for this study.

Chapter 3: Methodology, data acquisition systems interpretation approach, used parameter descriptions and all other associated tasks.

Chapter 4: Presents the main results of the plotting and interpretation with some remarks

Chapter 5: Discussion of study which has done so far.

Chapter 6: Recommendation for further work

Appendices: provide some supplementary information referred in the main report. Relevant information like formulas, raw and processed data, sample calculations site maps etc. are compiled in the appendix and referred whenever necessary.

2. Literature review

2.1 Introduction

An identification of quick clay in using different sounding methods have been the subject of interest for different reasons as explained earlier. Several attempts have been made by several researchers using analytical and theoretical approaches to understand the exact relations between the tip resistance and the slop of the inclination with depth and their interpretation strategies. Nevertheless, the different approaches used in the interpretation of the graph are generally so diversified both in terms of theoretical formulations as well as graphical interpretations that sometimes the graphical interpretation on the existence of the quick clay turns to different out comes when the sample is extracted and checked in the laboratory. Therefore; limited literature review, which were found to be relevant within the scope of the study are presented.

Even though there are different methods for quick clay mapping were used, in this study, the geotechnical sounding methods for mapping of the quick clay are studied. Therefore, the review focusing on the previous methods of mapping, relation of penetration resistance with depth, sleeve friction, inclination of the slope of the curve, pore pressure condition, sensitivity, activation of the clay, required incremental pressure and other related areas of interest are highlighted.

2.2 Basic geotechnical properties of quick clay

Quick clays differ from non-quick clays mainly concerning the relation between water content, consistency limits and activity(Rankka and others, 2004). Quick clay and clay with normal sensitivity can have the same type of mineralogy and that the difference in sensitivity was not related to the particle size distribution.

The differences in sensitivity are related to microstructural and physical/chemical conditions in the pore water in the clay(Talme, Pajuste, and Wenner, 1966).

2.3 Classification of quick clay

The sensitivity, S_t, is the relation between the undisturbed and the fully remolded shear strength. Quick clay is defined in Sweden as clay with a sensitivity of 50 or more and fully remolded shear strength of less than 0.4kPa (Lundstrom K., Larsson, and Dahlin, 2009). The latter value corresponds to a penetration of 20 mm by the 60 g cone with 60° tip angle in the fall-cone test. In Canada, sensitive clays are defined as clays with remolded shear strength of less than 1kPa and with a liquidity index of more than 1.2 (Robitaille and others, 2002).

In Norway, quick clays are defined as clays with remolded shear strength of less than 0.5kPa and sensitivity greater than 50 (Rolf Sandven, 2010).

2.4 Plasticity

Plastic soils are denoted and classified according to the value of the plasticity (or plasticity index) $I_P=W_l-W_P$. Compare to many international clays, Norwegian clays are generally considered to be of low plasticity, i.e. $I_P<10$(Rolf Sandven, 2010).

2.5 Liquidity index

For the description of the relation between the natural water content and the plastic range, the liquidity index is introduced.

$$I_L = \frac{W - W_p}{W_l - W_p} \qquad (2.2)$$

Where, I_l = Liquidity index

w_l = Liquid limit, %

w_P = Plastic limit, %

w = Natural water content %

From the above relation of indexes, when $I_l>1$ and $W>W_l$, this is a situation which is a typical an indication of quick clay behavior(Rolf Sandven, 2010).

2.6 Activity and clay mineral

(Skempton, 1953) stated the activity of clay mineral depends on the relation between plasticity index and clay content in clay. This relation was designated the activity of the clay, a_c, and is defined as:

$$a_c = \frac{I_p}{I_c} \qquad (2.3)$$

Where, I_P = plasticity index = $w_L–w_P$, %

w_L = liquid limit, %

w_P = plastic limit, %

l_c = clay content, percent of the total mass of fines,<0.2μm

Skempton also found that, the activity to be different for different clay minerals but fairly independent of the particle size distribution.

From his experiment, he found that the activity of all these clays fell in the range $0.15 < a_c \leq 0.65$ and the clays were thus designated as low-active clays. The activity of quick clay is normally less than 0.5.

2.7 Water content

The clay that sediments into a flaky structure develop a higher void ratio and water content compared to sediments with orientated structures. This would lead to a significant reduction in the liquid limit, whereas the natural water content normally remains constant. A characteristic of quick clay is that the water content is higher than the liquid limit. The liquid limit determined by fall-cone tests is defined as the water content at which the penetration of the 60g–60° cone into the remolded soil is 10 mm (Rankka and others, 2004). The corresponding remolded shear strength is about 1.5 kpa.

According to the Swedish definition of quick clay, the remolded shear strength must be equal to or less than 0.4 kpa. The water content therefore has to be higher than the liquid limit in quick clay. A larger decrease in liquid limit than in plastic limit implies that the plasticity index (I_p = w_L–w_p) decreases.

(Brand and Brenner, 1981) reports also that quick clays often have low values of the plasticity index ($I_p \approx 10 - 15$), which may be explained by a high content of low-active minerals. However, the quick clays found in Sweden often have considerably higher plasticity indices. The main changes in liquid limit, plasticity limit, remolded shear strength and sensitivity occur when the salt content is reduced below about 2 g/liter (Torrance, 1974).

2.8 Existing technics to map quick clay

In general, there are no adopted methods for quick clay mapping. In most cases, the existence of quick clay is observed from the results of the ordinary geotechnical sounding for different projects, mainly in the routine laboratory investigations which include determination of the sensitivity. The extent of the quick clay formation is then estimated from the existing results of the investigation and various arbitrary graphical considerations.

2.9 Geotechnical methods

2.9.1 Static pressure sounding

For the most commonly used sounding methods, correlations between sounding resistance and sensitivity were investigated by (Möller, 1982).

These methods were the traditional weight sounding test and static pressure sounding in which a weight sounding tip is connected to 25 mm rods and pushed down at a constant rate. The investigation was based on previous Norwegian observations that the slope of the penetration resistance versus depth curve (Figure 1) in clay could be linked to the sensitivity (Rygg, 1978).

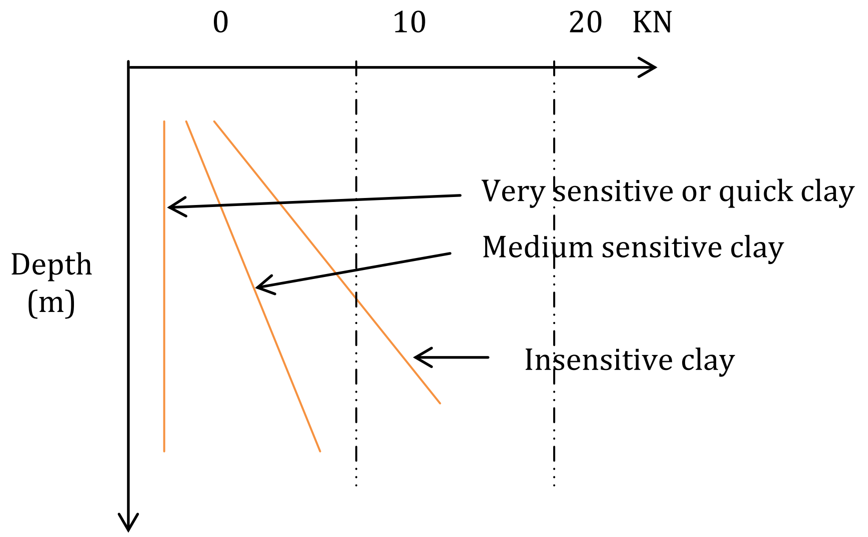


Figure 1 Basic Correlation between penetration resistance versus depth & sensitivity (Rygg, 1978).

For the static pressure sounding, another correlation was presented, in which the slope of the static force versus depth curve was related to the sensitivity, Figure 2. It was stated that if this curve had an inclination of less than 4 degrees from the vertical, the clay was likely to be highly sensitive or quick (Rankka and others, 2004). With the standard scales for presentation, this limit corresponds to an increase in penetration force of 0.07kN/m. This type of correlation has been used to some extent in subjective estimates of the relative sensitivity, although no specific limits have normally been applied.

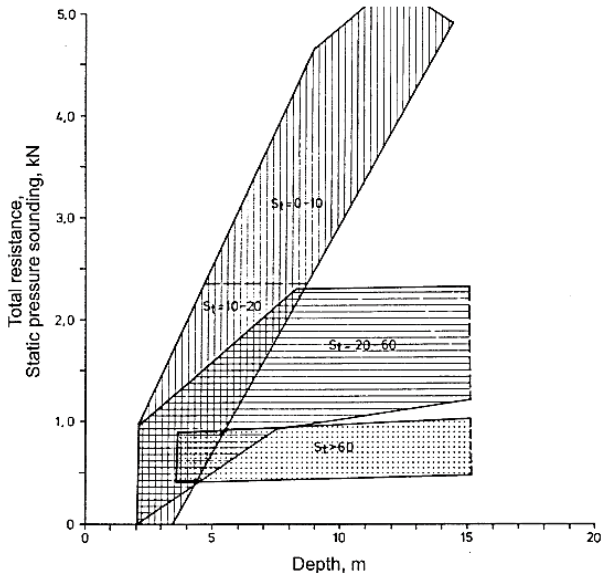


Figure 2. Penetration force versus depth for different ranges of sensitivity using static pressure sounding (After Möller and Bergdahl 1982).

However, these fields presuppose that the soil is fairly homogeneous throughout the profile and that there is a "normal" dry crust but no other layers causing high rod friction which lie on top of or are embedded in the clay. The utilization of these charts has therefore been limited due to the fact that it is very rare to have a homogenous layer over the total depth under investigation. For the static pressure sounding, another correlation was presented, in which the slope of the static force vs. depth curve was related to the sensitivity, see Figure 3.

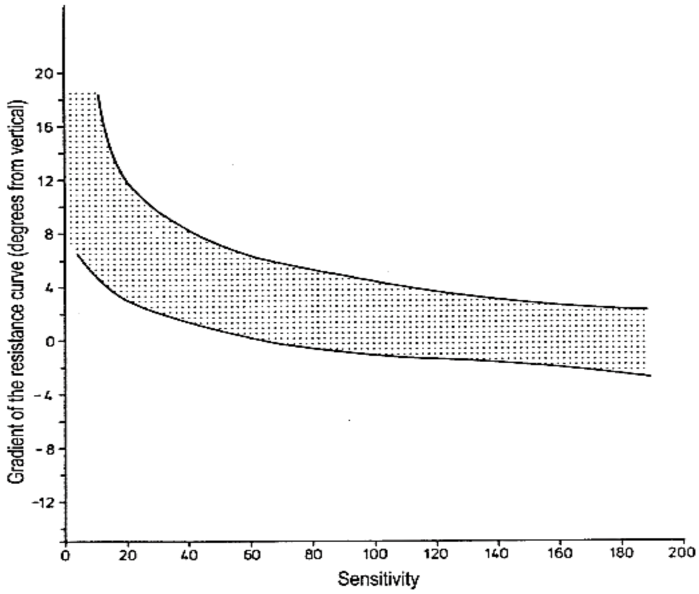


Figure 3. Slope of penetration resistance versus depth in relation to the sensitivity of the penetrated clay (After Möller and Bergdahl 1982).

It was stated that if this curve had an inclination of less than 4 degrees from the vertical, the clay was likely to be highly sensitive or quick. Generally, the higher the inclination from vertical tends to the lower the probability of having very sensitive or quick clay.

2.9.2 Geophysical methods

In marine clays that have been leached by fresh water, there is often a link between the salt content and the sensitivity of the soil, as well as between the salt content and the electrical resistivity of the soil. However, a low salt content does not necessarily imply that the clay is quick but only that a precondition for this exists (Torrance, 1979). Torrance found that the salt content had to be reduced below 2 g/liter (0.2%) before quick clay can be formed. The corresponding resistivity varies somewhat with the porosity of the soil since it is mainly the pore water that is conductive. (Penner, 1965). Laboratory studies on typical clay have shown that a content of 0.2% NaCl corresponds to a resistivity of between approximately 6 and 13 Ωm for the range of bulk densities of interest for quick clay formation.

2.9.3 Rotary pressure sounding

Rotary-pressure sounding is a Norwegian method developed in the 1960's (see Statens vegvesen, 1997). It uses a twisted tip and it is manufactured from a steel bar with a rectangular cross-section of 25 x 41 mm, which is twisted and then shaped into a conical tip at the lower end. One of the outer ridges of this screw is supplied with an extra hard welded top; see figure 4(a) the length of the tip is 225 mm and the projection of the cross-section has a diameter of 55 mm. The tip is attached to φ 36 mm sounding rods and pushed down into the soil at a rate of 3 ± 0.5 m/min while rotating at 25 ± 5 rpm. The drill rig shall provide a pushing force of at least 30 kN and a torque of about 1 kNm. Rotary pressure sounding was extensively used in Norway up to about 1990. Thereafter it has been gradually replaced by the now predominant total sounding method.

2.9.4 Total sounding

The total sounding method was developed in Norway in order to obtain a method that is sensitive enough to register all significant strata in a soil profile and their relative stiffness, and which is still able to penetrate all types of fills and soil layers as well as large blocks and bedrock (Statens vegvesen, 1997). The equipment is therefore supplied with a tip consisting of a specially designed drill bit with a diameter of 57 mm. See figure 4(b). This contains a spring loaded ball valve for the flushing medium, which prevents soil from entering the drill bit when this is driven without flushing but allows the flushing medium to flow out when so desired.

The drill bit is connected to hollow φ 45 mm steel rods of the same. The equipment can be driven into the soil in different ways depending on the penetration resistance. In soft soil layers, it is advanced in the same way as in rotary pressure sounding, i.e. at a rate of 3 ± 0.5 m/min and a rotation of 25 ± 5 rpm. The required pushing force and torque are also the same, i.e. 30 kN and 1 kNm, respectively.

2.9.5 Static pressure sounding

Static pressure sounding was developed in Sweden during the 1950's. See figure 4(c).The original equipment has a tip with a square cross-section of 34 x 34 mm giving a projected area of 1000 mm^2. The tip is connected to the drill rods through a slip coupling which enables the tip to move freely in relation to the rods over a distance of 50 – 100 mm in the pushing direction. The tip is pushed down into the soil at a constant rate of 1.2 m/min and the total pushing force is measured. After each stroke of 1 or 2 meters, new rods are attached and the rod assembly is lifted a distance corresponding to the stroke of the slip coupling. At the next stroke, the friction along the rods is measured first, followed by the total penetration force after the coupling has been re-engaged. In this way, the rod friction can be separated and the tip resistance evaluated. After the maximum pushing force has been reached, the system is rotated to achieve further penetration, if possible.

2.9.6 Cone penetration tests

The cone penetration test, CPT, normally measures cone resistance, sleeve friction and penetration pore pressure (Swedish Geotechnical Society, 1993). The sleeve friction is measured along the perimeter of an approximately 133 mm long portion of the probe located just above its conical tip. The probe has a diameter of 36 mm and a projected cross-sectional area of 1000 mm^2, see figure 4(d). It is attached to sounding rods, which in this case also had a diameter of 36 mm. The probe is pushed down into the soil at a rate of 1.2 m/min. The sleeve friction, like the friction along the rod system, should in principle be related to the remolded shear strength of the soil in the shear zone between the penetrating equipment and the soil.

However, the sleeve is located so close to the tip that, depending on the work required to completely remolding the soil, the soil will normally be only partly remolded here. Because of practical limitations, the accuracy of the measurements is also restricted. In highly sensitive clays, most of the recorded friction is an effect of the pore pressures acting on the end surfaces of the sleeve. Even after careful calibration and correction for all known sources of error, the accuracy of the measurements will not be better than ± 2 kPa. This should be put in relation to the limit in the classification, where quick clay has a remolded shear strength of ≤ 0.4 kPa.

The total penetration force is normally not measured in a CPT test. However, this can be done fairly easily if the drill rig is equipped for any penetration test where the pushing force is measured in the rig itself, e.g. rotary pressure sounding, total sounding or static pressure sounding. In this case, the weight of the equipment can be added and the tip resistance subtracted from the total penetration force. A sounding is obtained in which both the friction at the tip and the friction along the perimeter of the whole equipment are obtained as functions of penetration depth.

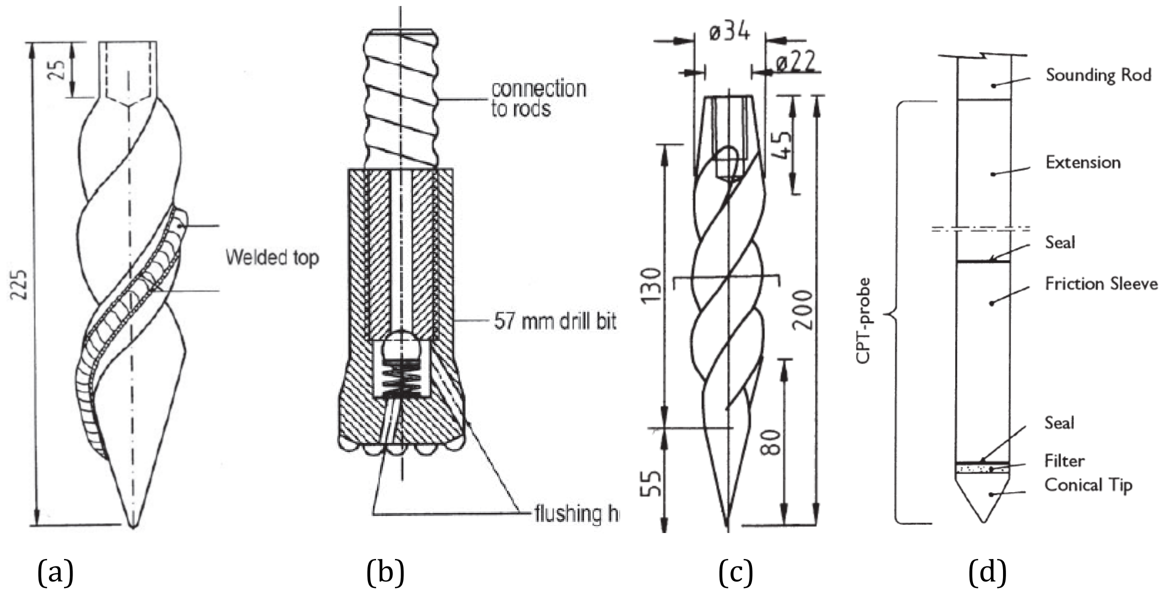


Figure 4. (a) Rotary pressure sounding, (b) total sounding, (c) static pressure sounding and (d) cone penetration test sounding.

2.9.7 Field vane tests

The field vane test (Swedish Geotechnical Society, 1993) is the only type of in situ test that has so far been used to estimate both the undisturbed and remolded undrained shear strength and the sensitivity. The method is well established for determination of the undisturbed undrained shear strength in clay. The required accuracy of the shear strength determination in soft to medium stiff clay is normally ± 1 kPa. To achieve this accuracy, the friction in the system and along the rods has to be measured, usually by means of a slip coupling between the rods and the vane. This is the case also for vane equipment using a casing around the rods.

For an accurate estimate of the remolded shear strength in highly sensitive clay, the accuracy should be about 10 times better than what is normally required and achievable. In the normal procedure of measuring the remolded shear strength, the recording instrument is disengaged after determining the undisturbed shear strength. The rods and the vane are then rotated about 20 turns, after which the rods are turned back to open up the slip coupling.

The recording instrument is then re-engaged and the rods are turned slowly to measure the rod friction before the slip coupling is closed and the total torque recorded. The operations from the end of rotation of the vane until remolded failure for vane and rods is reached take a certain time. A large number of parallel investigations with both field vane tests and fall cone tests have been performed in the extensive investigation in soft sensitive clay.

2.9.8 Fall-cone tests

The usual way of estimating the remolded shear strength in clay is to use the fall-cone test (Lundstrom K., Larsson, and Dahlin, 2009) . This test can be used to determine both undisturbed and remolded shear strength, and the former determination requires undisturbed samples. If such samples are available, the sensitivity can be determined based on the fall-cone test results alone. However, undisturbed sampling is time-consuming and costly, particularly in quick clays. A possible alternative is therefore to take disturbed samples and use the fall-cone test to determine the parameters remolded shear strength and liquid limit, which are not sensitive to disturbance. The remolded shear strength can then be compared to the undisturbed shear strength that is evaluated from field vane tests or CPT tests, after which the sensitivity can be calculated.

2.9 Comparison of the sounding methods

The static pressure sounding: The test uses the simplest and most easily operated equipment. Since the twisted tip with an overall diameter of 35 mm is pushed straight down, it causes a considerable remolding of the soil. As it is considerably larger in diameter than the φ 25 mm push rods, it also acts as a friction reducing expander of the drill hole.

Although it uses the lightest type of equipment, it is also proved to be the type that is most prone to sink under its own weight without any extra pushing force in profiles with quick clays.

The rotary pressure sounding: The equipment is similar in appearance, but with a φ 55 mm overall diameter of the tip and φ 36 mm sounding rods. The equipment is thus heavier, but the test takes less time since the penetration rate is 3 m/min compared to 1.2 /min. The pitch of the twisted tip and the rate of rotation match approximately the rate of penetration, and the equipment is thereby more or less screwed down into the profile. The remolding of the soil and the relative expansion of the hole by the tip is thereby reduced. On the other hand, the simultaneous rotation and pushing entails that only part of the friction force along the rods is taken up and recorded as a vertical force. The test method is in most cases being replaced by total sounding, but experience in estimating the sensitivity of the soil is larger with this method.

Total sounding: Uses the heaviest equipment, which apart from a heavy drill rig also requires a supply of high-pressure flushing water or compressed air. The rate of penetration is the same as for rotary pressure sounding and the ability to penetrate also coarser and firmer layers widely surpasses that of any of the other methods. Because of the adapted modes of penetration during sounding, the resolution in the soft layers can be expected to be about the same as that for rotary pressure sounding. The diameter of the drill bit is 57 mm and the rods have a diameter of 45 mm. The drill bit thereby expands the hole and reduces the friction along the rods. The rotating drill bit also causes remolding, but it is difficult to estimate how much. The friction in the soil layers higher up decreases gradually because of further remolding as the rod system passes through and a certain decrease can also be expected as the hole becomes enlarged by wobbling effects from rotating rods, particularly in friction soils. On the other hand, there may be a certain migration of pore water from the smeared zone along the rods and thereby a gradual increase in remolded strength. When studying the trend of total force versus depth, it has to be assumed that these effects are negligible and that variations in the tip resistance due to variations in the nature of the clay are also negligible.

This is not always the case, particularly in transition zones between the dry crust or any other stiffer or coarser overlying soil and the soft clay below or when entering the silty bottom layers that occur frequently in some clay profiles.

The CPTu test: With additional measurement of the total penetration force is a considerably more elaborate method, which requires time for preparation of the probe. On the other hand, it yields much more detailed information on the soil in the profile than any of the other methods.

Once the test is started, it continues at the same rate as static pressure sounding, i.e. at 1.2m/min. The test is performed without rotation and, when the rods have the same diameter as the probe, it creates the least disturbance. The friction measured against the sleeve just above the tip is therefore normally measured in only partly remolded soil. Since the tip resistance is measured and subtracted from the total penetration force, all errors in the rod friction related to the tip resistance and its variations are eliminated.

The dual measurement of the friction, at the tip and along the rod assembly respectively, makes it possible to check that variations in the total rod friction that are assumed to be related to additional friction at the lower end of the assembly are matched by a similar pattern of the friction measured here.

The continuous profiles of CPTu data provide excellent information on soil stratigraphy. (Sully and others, 1999) demonstrated that CPTu is the best available tool for detecting thin permeable layers.

CPTWD (Cone Penetration Test While Drilling): It represents integration of wire-line drilling system, standard and modified piezo-cone, while drilling. During the CPTWD test the cone is protruding in front of the drill bit during drilling in the same way as a corer; CPTu data are stored in memory unit. At the same time as the CPTu data are logged, drilling parameters (MWD, monitor while drilling) are also recorded. The system allows for the change between CPTu testing, continuous core drilling, down-hole testing and non-coring drilling with MWD. The combination of CPTu parameters and drilling parameters can be a very powerful basis for interpretation of the data. The advantages of this system compared to the other down-hole type CPTu is that much longer strokes than the normal can be made. In addition, the information from the drilling parameters is very useful, especially in hard formations where CPTu cannot be performed(Sacchetto and others, 2004).

2.10 Identification of quick clay with geotechnical methods

Certain correlations between sounding resistance and sensitivity have been previously noted. For example, (Möller, 1982),showed that the slope of the penetration resistance versus depth curve in clay can be linked to the sensitivity. Tentative charts for sounding resistances versus depth have been proposed. Möller and Bergdahl (1982) proposed also for the static pressure sounding four different ranges of sensitivity of the static force–depth curve, which are previously shown in figure 2. They stated that if the inclination of the curve corresponds to an increase in penetration force less than 0.07kN/m, the clay is likely to be highly sensitive or quick. To investigate this further, rotary pressure sounding, total sounding, static pressure sounding, and cone penetration tests were used in this investigation.

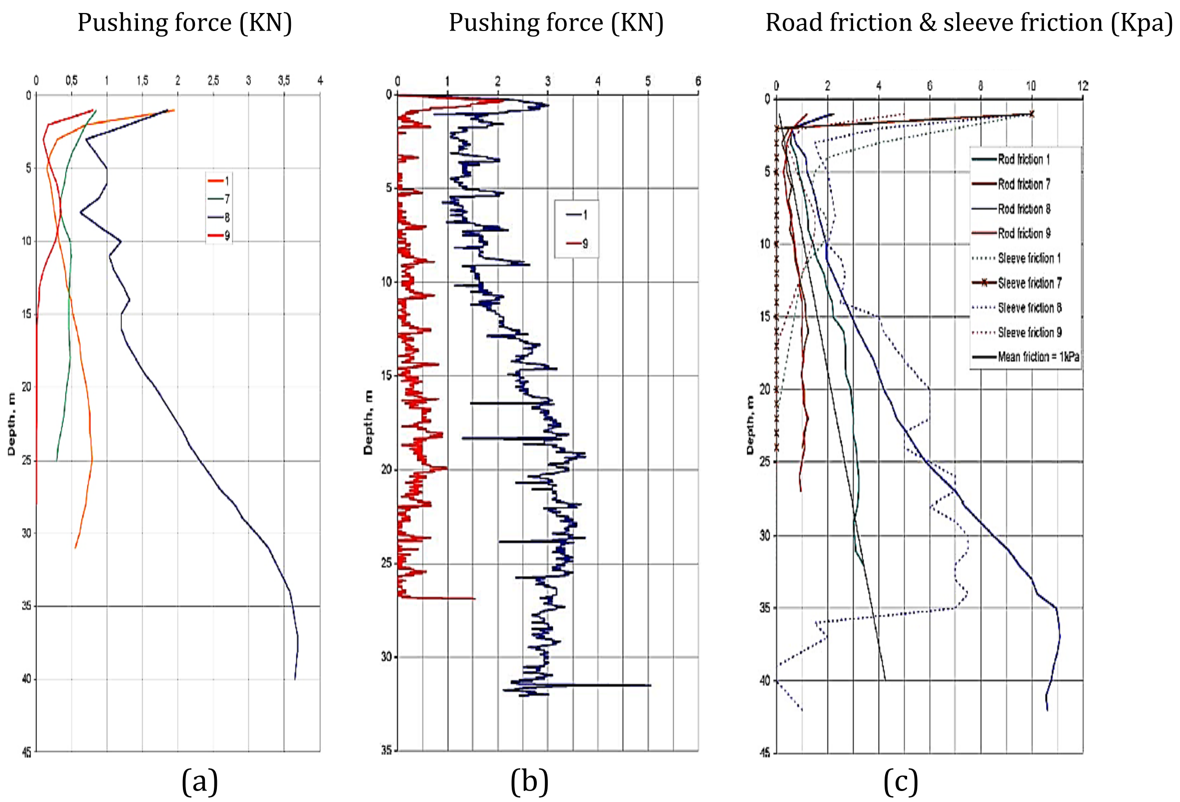


Figure 5. (a) Results from rotary soundings, (b) total sounding and (c) CPTu at a test site Skepplanda (Sweden)

The results from rotary pressure sounding figure 5(a) and total soundings figure 5(b) show approximately the same picture, though the rotary pressure soundings show somewhat less detail. Both types of equipment sank under their own weight for part of the profile in the most sensitive clay. For the CPTs, the results have been corrected by subtracting the measured tip resistance from the total penetration force and adding the weight of the rods. The curves have also been smoothed to remove the enhanced friction due to temporary stops in the penetration. The rod friction is generally higher than for the other sounding methods, which can be related to the considerably lower remolding by the tip. In Figure 5(c), a guiding line corresponding to an average rod friction of 1kPa has been inserted. An inclination steeper than this line indicates that the clay is highly sensitive and probably quick, and parts in which the curves are vertical or almost vertical indicate quick or highly quick clays. The general picture is verified by the measured sleeve friction, which is zero or almost zero in the parts with highly quick clays and generally less than 2kPa in the parts with highly sensitive to quick clays. When judging the absolute values of the sleeve friction, it should be considered that these may be expected to be considerably higher than the completely remolded shear strength.

The results of the CPTu also indicate that there is denser clay at the bottom of the clay profiles, with embedded thin silt layers at the very bottom. The quick clay in the deeper clay profiles is located mainly in this layer (Lundstrom K., Larsson, and Dahlin, 2009).

2.11 Correlation of slope of pushing force to depth

Some studies that are made so far on the identification of quick clay methods has shown that there is a general correlation between the slope of the pushing force to depth curve and the sensitivity of the soil at the same depth (Figure. 6 a–d).

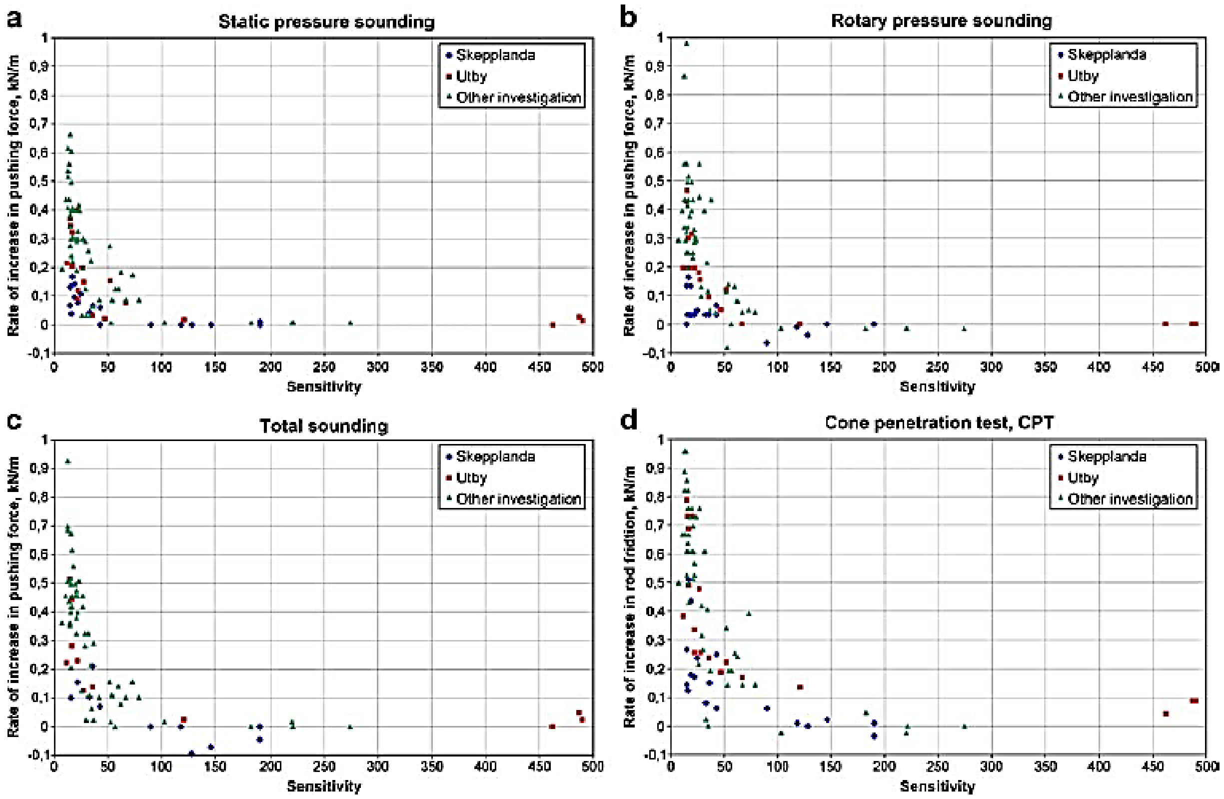
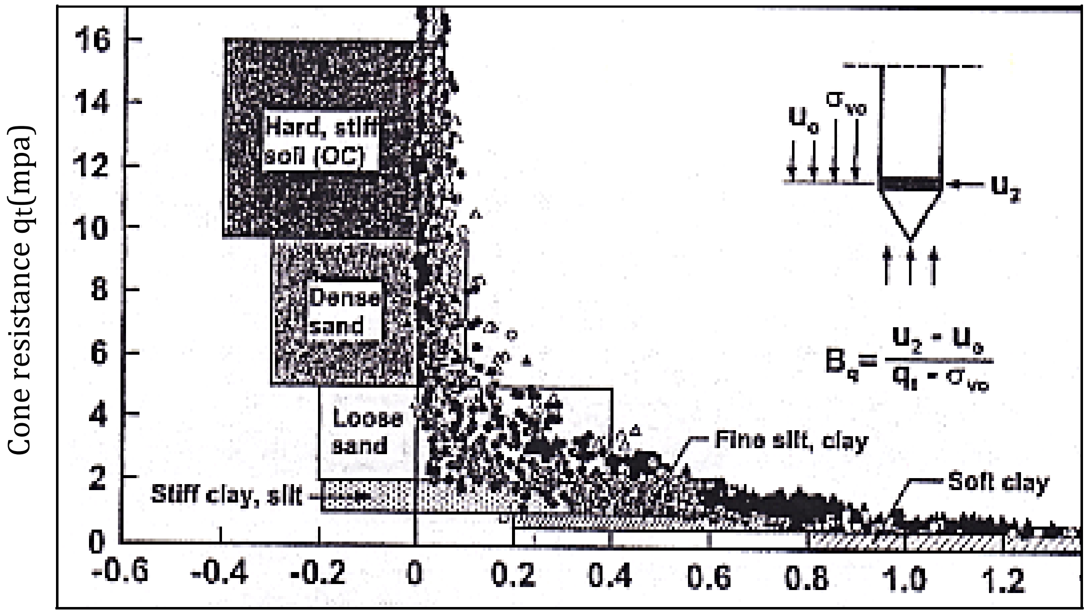


Figure 6 (a) Static pressure sounding resistance and sensitivity, (b) rotary pressure sounding resistance and sensitivity, (c) shows total sounding resistance and sensitivity, (d) corrected rod friction (from CPT) and sensitivity (Lundstrom K., Larsson, and Dahlin, 2009)

However, since there is no direct connection between pushing force and sensitivity, there is a large variation in sensitivity for any given slope of the sounding curves, except for the very flattest. The correlations can therefore be used mainly for a rough division of the soil into sensitivity class. No precise rules can be given for the way in which this should be done because the correlation is only indirect and depends on soil type, equipment, and test performance (Lundstrom K., Larsson, and Dahlin, 2009).

2.12 Classification of soil type

Several classification diagrams have been developed for interpretation of soil type based on CPTu recordings. Figure 7 shows a classification diagram developed at NTNU which introduces the correlation between cone resistance qt and pore pressure ratio Bq as entry parameters. The diagram is empirically based on Norwegian CPTu records, including data both from onshore and offshore investigations. The diagram implies that quick clay layer could be identified as pore pressure ratio Bq gets greater than 1 and cone resistance qt gets less than 1mpa.

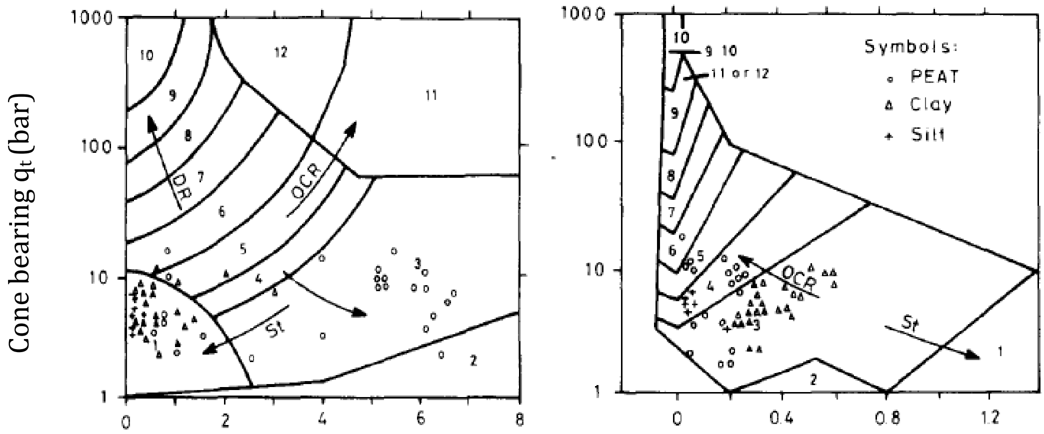


Pore pressure ratio $B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}}$

Figure 7. Diagram for classification of soil type from CPTu recordings (Sandven R, 1995)

2.13 The Robertson and Campanella chart

(Campanella and Robertson, 1988) Considered that classification cannot always be reliably based on q_t (or q_c) and B_q alone, in the same way that the combination of q_t (or q_c) and f_d is not always universally reliable. They use all three parameters (q_t,f_s, u) in the form of q_t-B_q and B_q-f_s charts as shown in Figure 7.(a and b)



(a) Friction ratio (R_f) (b) Pore pressure ratio (B_q)

Zone	Soil behavior type	Zone	Soil behavior type
1	SENSITIVE FINE GRAINED	7	SILTY SAND TO SANDY SILT
2	ORGANIC MATERIAL	8	SAND TO SILTY SAND
3	CLAY	9	SAND
4	SILTY CLAY TO CLAY	10	GRAVELLY SAND TO SAND
5	CLAYEY SILT TO SILTY CLAY	11	VERRY STIFF FINE GRAINED
6	SANDY SILT TO CLAYEY SILT	12	SAND TO CLAYEY SAND

Figure 8. Soil classifications (after Robertson & Capanella)

They point out that sometimes one soil layer will fall within different zones on each chart. In these cases engineering judgment is required for a correct classification. From their experience, this is the best one of the three charts. However, for Dutch soils, only 41% of the total data are correct within both (a) and (b) of Figure 7. The situation is better for Figure 7(b) alone, but some scatter exists as well; nearly 80% is correct. They found out that most of these incorrect points are corresponding to the shallow zone within 3-5 m depth from the ground surface. Note that the influence of the depth on the parameter q_t was not taken into account in these charts.

2.14 Correlations between q_c and vane shear strength

Vane shear strength and cone resistance, q_c, for Scandinavian soft clay has been compared for six different sites in Norway and Sweden. At five of the sites, three in *Drammen*, one in *Onsay*, and one in *Ggteborg*, the clays have been sedimented in an entirely marin environment. At the *Skå-Edeby* site the conditions have been marine-brackish or brackish-marine, i.e. with more salt content. When compared with field vane shear strength, the cone factor, N_k in the formula:

$$q_c = N_k.\tau_f + \gamma.z \qquad \text{(Sandven R, 1995)} \qquad (2.13)$$

Where, q_c = cone resistance (kpa)
N_k = cone factor

τ = undrained shear strength (kpa)
γ = total unit weight of soil (kpa)
z = depth of penetration (m)

Table 2. 1 Summary of N_k values after site test (Lunne, Eide, and De Ruiter, 1976)

Test site	Depth (m)	Range $\tau_f(t/m^2)$	Plasticity $I_p(\%)$	Sensitivity	Cone factor N_k
Sundland Drammen	4–9	2–2.5	22–28	10–15	17–18
	9–14	2–4.5	~10	~2	20
	14–22	2.5–4	~10	3–4	15.5
Dansvigs gate Drammen	5–10	2–3	20–25	6–9	14–15
	11–30	2–4	10–11	2–4	14–16
Børresens gate Drammen	5.5–12	3–2	~15	15–25	16–20
	12–30	1.3–2.5	~5	50–160	20–24
Onsøy	1–9	1.2–1.4	20–30	5–10	16–18
	10–20	1.8–4.8	35–40	4–7	13–18
Skå-Edeby	1–4	0.6–1.2	45–80	6–10	8–9
	4–12	0.8–2.0	30–50	10–15	10–12
Gøteborg	3–10	1.5–2.5	50–60	15–24	13.5–14.5
	10–21	2.5–4.2	50–55	13–19	13–14
	21–30	4.5–5.5	~40	13–17	13–14

N_k value varies between 13 and 24 for the five marine clays. For the *Skå-Edeby* clay the N_k values lie in the range 8 to 12 at different depths. Corrections of field vane shear strength result, for the five marine clays, in N_k values between 15 and 19 with an average of 17. This N_k value can be used for Scandinavian marine normally consolidated clays, but may not be valid in other types of clays. An example of this is the Skå-Edeby brackish-marine clay where the corrected N_k values fall between 11 and 13. Theoretically, the N_k; factor should be close to 9 for clays that are not very sensitive. (Skempton, 1951).

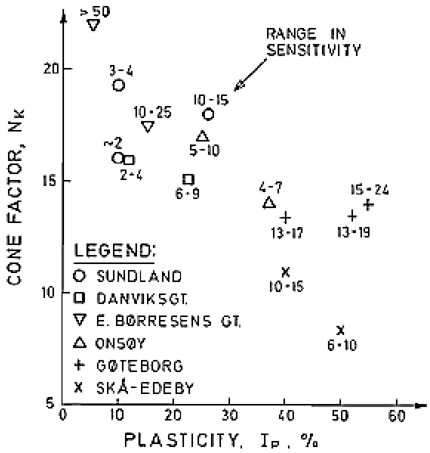


Figure 9. Summary of N_k values for all sites (Lunne, Eide, and De Ruiter, 1976).

Based on back calculation of failures below embankments and in cuttings in soft marine clays, some experience exists on correlation between field shear strength from embankment failures and vane shear strength values.

A correction of the vane shear strength based on plasticity index has been proposed (Bjerrum, 1967). Introducing this correction the N_k, factor varies between 15 and 19 with an average of 17 in the marine clays tested and between 11 and 13 for the brackish soft clay at Skå-Edeby. From this it is suggested that an N_k, factor of 17 can be used to correlate cone resistance to undrained shear strength for Scandinavian marine normally consolidated clays. However, this N_k, value should not be used uncritically in other types of clays, as for instance the Skå Edeby clay (Lunne, Eide, and De Ruiter, 1976).

2.15 Effects of sensitivity and plasticity index

Sensitivity (S_t) can be defined as the ratio of undisturbed undrained shear strength to totally remold undrained shear strength and it can also be interpreted with the use of sleeve friction (f_s) data from CPT where f_s represent equally to remolded undrained shear strength (Robertson, 2010). The relationship can be given in percent as shown in Eq-2.15.

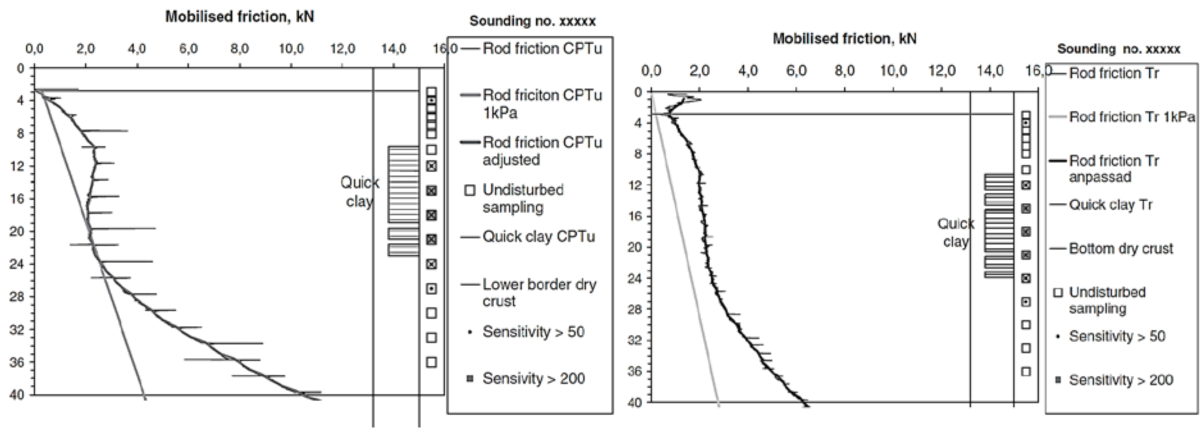
$$S_t = \frac{N_s}{R_f} \tag{2.15}$$

Where, N_s is a constant and R_f is friction ratio.

According to (Lunne, Christoffersen, and Tjelta, 1986), for the value of N_s, an average value of 7.5 is selected from the range of 5 to 10 using the non-normalized friction ratio (R_f). N_s value of 7.3 and 7.1 was suggested by (Mayne, 2007) and (Robertson, 2009) respectively.

2.16 Estimation of quick clay from CPTu and static pressure sounding

Estimation of quick clay from static pressure sounding and CPTu is based on measurements of the penetration resistance of the soil, i.e. the measured thrust force on the rods (K .Lundstrom, Larsson.R, and Dahlin.T., 2009). The measured penetration resistance complemented by the weight of the rods and, for the CPTu, that reduced by the tip resistance, corresponds to the rod friction (in kN). This rod friction is compared with a rod friction of 1 kPa. Where the inclination of the curve for rod friction is less than the inclination of the curve for 1 kPa rod friction, the clay is classified as quick. The result from a CPTu in quick clay is presented in Figure 9(a) and the result from a static pressure sounding at the same point is presented in Figure 9(b).



(a) (b)

Figure 10. (a) Estimated quick clay results from CPTu sounding, (b) from static pressure sounding (K .Lundstrom, Larsson.R, and Dahlin.T., 2009)

Results from laboratory testing are included for comparison. Shading to the right in the diagram shows the parts of the soil profile that were estimated as quick clay. Based on this estimation an engineering assessment of the depth of quick clay was made.

When determination of sensitivity and remolded shear strength from undisturbed sampling is available, this can also be presented in the diagram. In both diagrams peaks in the curves are shown at regular intervals. These occur when the sounding is stopped to lengthen the rods since the rods 'take root' in the clay. The result from a CPTu sounding in non-quick clay is presented in Figure 10.

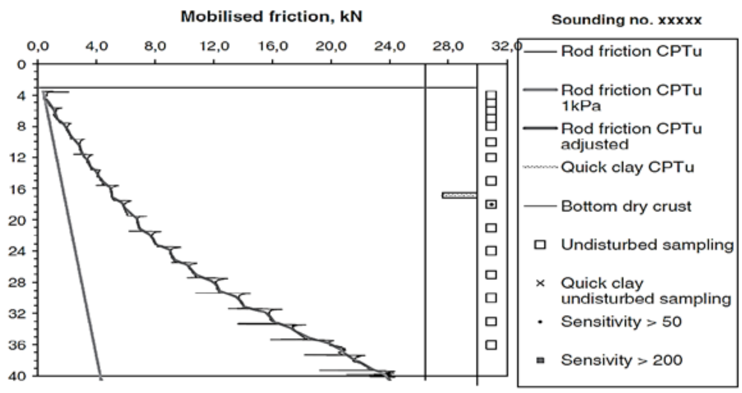


Figure 11. Result from a CPTu sounding in non-quick clay is presented (K .Lundstrom, Larsson.R, and Dahlin.T., 2009)

As it was stated after the investigation made at the Göta River in Sweden (K .Lundstrom, Larsson.R, and Dahlin.T., 2009). It was important to evaluate the accuracy of this method for estimation of quick clay before using it for mapping of quick clay within all areas of the site. Consequently, a comparison was made between quick clay determined by means of fall-cone tests in the laboratory and quick clay estimated from the rod friction of the CPTu and from the static pressure sounding, Figure 12.

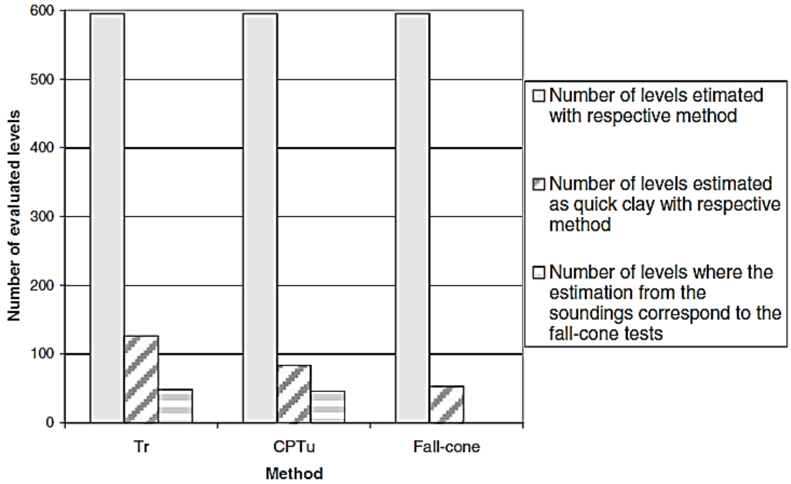


Figure 12. Estimation of quick clay from CPTu and static pressure sounding in comparison with laboratory tests (K .Lundstrom, Larsson.R, and Dahlin.T., 2009).

In this comparison, a total of 595 sampling levels where fall-cone tests had been carried out were evaluated. From these, 53 levels of quick clay were determined using fall-cone tests. The CPTu identified 46 of these 53 as being quick clay. In addition, 37 more levels were identified as quick clay, which were not determined as quick clay by the fall-cone test. With the static pressure sounding, 48 of the 53 levels with quick clay were classified as quick clay. In addition, 78 more levels were classified as quick clay by the static pressure sounding, which were not determined as quick clay using fall-cone tests.

The results show that almost all levels classified as quick clay using fall-cone tests were also classified as quick clay using the sounding methods. However, both sounding methods also identify quick clay at levels where the clay is not quick according to the fall-cone test, leading to a probable overestimation of the extent of quick clay. The CPTu is more accurate than the static pressure sounding. The main reason is probably that the tip resistance is measured using the CPTu and can be subtracted from the total penetration force, which is not done with the static pressure sounding.

In addition, the much larger diameter of the tip (35 mm) of the static pressure sounding compared to that of the rods (22 mm) makes it expand the drill hole and reduce the rod friction. After the (K .Lundstrom, Larsson.R, and Dahlin.T., 2009) investigations, the results confirm that the CPTu offers good agreement with determinations of sensitivity using the fall-cone test. As the CPTu is often used in clayey soils for stratification and estimation of the undrained shear strength of the clay, estimation of quick clay from rod friction gives additional information about the clay at the points where CPTu is carried out primarily for other purposes. The comparison within the Gota River investigation shows that, generally, estimation of rod friction indicates slightly more quick clay than sensitivity determinations in the laboratory. The static pressure sounding is less precise than the CPTu, and indicates more quick clay. Within the separate study at Frastad, estimation of quick clay from rod friction of the CPTu indicated quick clay similar to the fall-cone tests, but with slightly different boundaries.

2.17 Brittle clays

Clays are classified based on their response when it is tested using different testing methods in the laboratory. Using the fall-cone test, brittle clays are typically classified in terms of sensitivity, S_t, which is the ratio of the intact shear strength (C_i) to the corresponding remolded shear strength (C_r) measured using the fall-cone test at the same water content(Torrance, 1974). According to the current geotechnical code, issued by the Norwegian Water Resources and Energy Directorate (NVE), Norwegian clays, that have $S_t \geq 15$ and a $C_r \leq 2$kPa are treated as brittle clay.

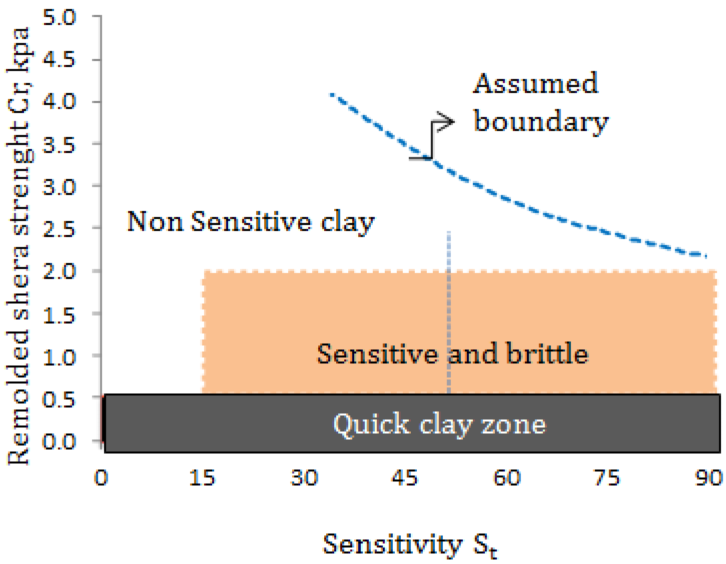


Figure 13. Classification of none sensitive, brittle and quick clays after (NVE guide line, 2011)

As previously stated, the Norwegian criteria of a clay to be considered as a quick clay is to have remolded strength, Cr, $\leq$ 0.5kpa and a sensitivity, S_t, $\geq$ 50. This shows that the range of quick clay consideration is between Cr$\leq$2kpa and St $\geq$ 15.

2.18 Overconsolidation Ratio (OCR)

According to (Lunne, Robertson, and Powell,),Over consolidation ratio (OCR) are typically defined as the ratio of the maximum past effective consolidation stress (σ'_p) and the present effective overburden stress, σ'_{vo}. Stress state and history in the soft subsoil under the embankment were evaluated with CPTu.

Soil overconsolidation can be determined from CPTu data according to formula (Lunne, Robertson, and Powell,):

$$OCR = \frac{a(q_t - \sigma_{vo})}{\sigma_{vo}'} \qquad (2.18)$$

Where,

a – is a coefficient from 0.2 to 0.5 related to plasticity index. (Lunne, Robertson, and Powell,) suggest that the average value of a coefficient is 0.3

qt- Corrected cone resistance

σ_{vo} and σ'_{vo} - are total overburden stress and effective overburden stress, respectively.

2.19 Some possible influence factors of interpretations

One of the possible influences on the interpretation of the plots is lamination of clay. Lamination is occurred when the clay is interbedded with silt and/or sand lenses (2013).

The other factor is the artesian water pressure. The pore pressure situation in the clay is probably affected by a high permeability in the overlying layers of sand and silt, the water level in the river and the underlying layer of till (Rankka and others, 2004). The rate of the leaching process is affected strongly by the hydraulic gradient. Areas with a high artesian ground water pressure therefore have better prerequisites for quick clay formation than areas with hydrostatic ground water conditions (Rankka and others, 2004).

If the clay deposit is unusually thick and has been affected by the river stream during sedimentation under marine environment, the area could be subjected to artesian pressure from an aquifer below; thereby the lower part of the clay layer has been leached, that could lead to very low shear strength and low OCR (Kim, 2008).

Quick clays are thus found mostly in areas close to valley sides where bare rock becomes visible and above (and below) thick and continuous deposits of coarse sediments (Rankka and others, 2004).

3. Methodology

3.1 Introduction

Large areas in Norway are prone to landslides in sensitive or quick marine clays. Landslides can be triggered naturally, but human activity is often an important factor (Rolf Sandven and Inger-Lise Solberg, 2013). Slope failures in marine deposits occur regularly, however with varying sizes and consequences. Fortunately, landslide disasters with remolding of large volumes of quick clay occur very rarely. In Norway, presence of quick clay is usually detected by geotechnical soundings and undisturbed sampling in traditional site-investigation schemes. Laboratory testing on retrieved samples is hence considered to be the most reliable detection. Even though many site investigations are made all over Norway, for this study, data are taken from different sites which believe to be helpful for the thesis. Åby site, southern Norway, Kaldvelladalen and Fallan Mid-Norway, Byneset west of Trondheim, Tiller southern Trondheim and E6Harran are the sites selected for this study.

This chapter included the research strategy that can give brief understanding of the aim of study. It is then followed by data collection where it includes all the materials used, step by step approaches both for laboratory tests and field data such as CPTu, borehole data and total soundings. Then the data analysis part included every detail of the system that is used to draw meaningful conclusions from the data collected.

3.2 Parameter description

Basic parameters obtained from CPTu sounding according to (Rolf.Larsson, 2007), are the cone resistance (q_t or q_c), shaft friction (f_t or f_c) and pore water pressure (u).

- Cone resistance (q) is defined as the total axial force divided by the cross section area of the tip. Two different denominations exist for the cone resistance, q_c and q_t. Unadjusted cone resistance for pore water pressures acting on the tip is q_c, and q_t is the adjusted cone resistance. Cone resistance (q_c) and the sleeve friction (f_s) values which are measured from cone penetration test have to be corrected for pore pressure effects in order to have a tangible data for interpretation. (Campanella, Gillespie, and Robertson, 1981;Baligh and others, 1981).

The corrected cone resistance according to (Lunne, Robertson, and Powell, 1997) given as:

$$q_t = q_c + u_2\ (1\text{-}a) \qquad (3.1)$$

Where, 'a' is the ratio of the cross sectional area of the load shaft divided by the projected area of the cone.

- Shaft friction (f) is defined as the total friction force acting on the friction sleeve divided by the shaft area of the sleeve. As for the tip resistance, two denominations exist for the shaft friction, f_s and ft. The sleeve friction f_s, is unadjusted for pore water pressures and f_t is the adjusted sleeve friction.

- Pore pressure (u) is the sum of the generated pore pressure (Δu) caused by the probe during sounding and the initial in-situ pore pressure (u_0). The generated pore pressure can be positive or negative depending on soil properties and filter media location on the probe (Rolf.Larsson, 2007). The generated pore pressure at normal filter placement, above the probe tip, is defined as Δu_2.

For the interpretation of measurement results, basic parameters like in-situ pore pressure (u_0) and in-situ vertical pressure (σ_{v0}) are needed. Relations between the basic parameters discussed are used for interpretation of the results.

For preliminary interpretation and soil classification the parameters given below are often used (R.Larson, 1993).

Generated pore pressure $\Delta u = u - u_0$ (3.2)

Friction ratio $R_{ft} = (f_t/q_t)$ (3.3)

Pore pressure ratio $Bq = \Delta u_2/(q_t - \sigma_{v0})$ (3.4)

3.3 Cone resistance number N_m

N_m is the cone resistance number and can be interpreted by the following equation

$$N_m = \frac{q_t - \sigma_{vo}}{\sigma'_{vo} - a} \qquad (3.5)$$

Where: a- is soil attraction and q_t, σ_{vo} and σ'_{vo} are as interpreted in section 2.18.

To compute N_m, the value of attraction (a) is necessary in addition to CPTu data as shown in equation 3.5. Therefore, attraction value can be obtained from triaxial tests, from the trend of q_t versus σ'_{vo} diagram of (Senneset and Janbu, 1985) or from general experience. In this thesis a=15 is taken as a representative value of attraction for Scandinavian soil.

3.4 Material used and procedures

Analysis of raw CPTu data such as sleeve friction (f_s), uncorrected cone resistance (q_c) and pore pressure measured behind the cone (u_2) were applied by cone penetration tests where a cone on the end of a series of rod is pushed into the ground at a constant rate of 2cm/second.
Those parameters helped in identifying the nature and sequence of subsurface strata, ground water condition, sensitivity and physical and mechanical behavior of soils.

A cone with a 10 cm^2 base area cone tip with an apex angle of 60 degrees is accepted as standard and has been specified in the European and American Standards. The friction sleeve, located above the conical tip, has a standard surface area of 150 cm^2. The porous filter of the piezo element is 5 mm thick.

3.5 CPTu, Total & Rotary sounding with lab data interpretations methods

Interpretation of CPTu measurements was made using SigmaPlot and Excel spreadsheet software. The selected raw data of the CPTu soundings were processed and prepared for further interpretation. At the beginning, corrections of raw data were made such as net cone area ratio, reduction of false measurements and elimination of thin layers. As there were no dissipation test results, pore pressure measurements from piezometers were used for the calculation of in situ pore pressure (u_0). Once the CPTu data are corrected for pressure effects and the in situ pore pressure is taken into account and the data from the total sounding is plotted, it will be easier to interpret and to obtain useful output which is helpful to meet the objective of the study together with laboratory tests. This is an important part of the research where it explains in detail all the approaches used to determine the location and property of the quick clay layer. In the stratigraphic Profiling the basic signatures to look for in measured data are:

- Shape and magnitude of q_t profile – e.g., high in dense sand, low in soft clay
- Shape of u profile and magnitude, especially relative to equilibrium pore pressure profile e.g., high in soft clay, $\Delta u = 0$ in medium density sand.
- Magnitude of R_f relative to that of q_t – e.g., if high and coupled with low q_t implies soft clay.
- Total and rotary sounding verse depth plot, almost vertical for very soft or quick clay.

4. Study area description, data plotting and Interpretation

4.1 Åby Site

One of the sites selected for investigation was Åby municipality in Bamble Telemark southern Norway. In August 31, 2011 a quick clay slide has happened in Åby, close to County Road 208. The landslide was triggered by erosion from the Åby river. The land slide was about 40 meters wide, 20 meters long and has a drop from top to the watercourse of approximately 6-7 meters. The locations of the 9-CPTu tests are shown in figure-6 .A detail map of the study area is found in appendices. After two avalanche incidents in 1952 and 1999 geotechnical investigations were made by Statens Vegvesen.

A geotechnical investigations was conducted which showed around 4 meters thick layer of sand and silt over clay to about 30 meters depth. There are several documented clay slides in the area over the last 60 years. See the map on figure 14.

4.1.1 Geological history

The area is a large reserve of soft marine silt and clay. Salt from seawater binds clay particles together and soil type of high strength with an open structure. Until today, the area rose about 45m, and old marine sediments are the present landscapes. The salt from seawater being washed out and thus, the quick clay formed, which in its disturbed condition is liquid. This allows a retrogressive type of soil movement may develop.

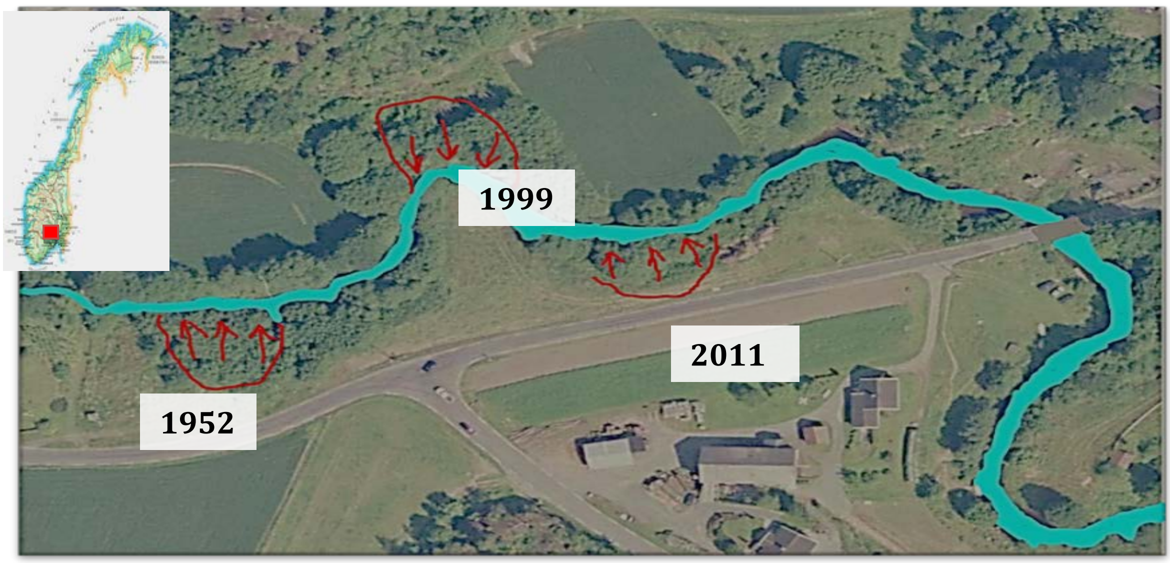


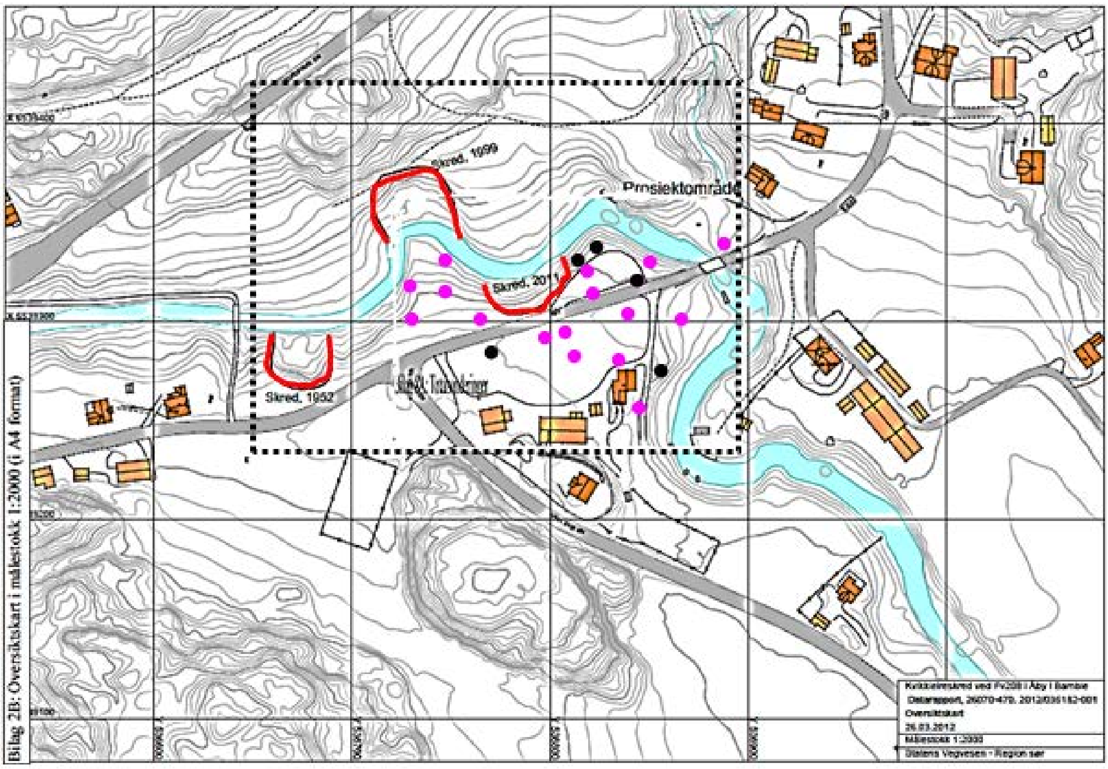
Figure 14. Study area at Åby with locations of previous slides (www.Gulesider.no)

4.1.2 Research strategy

To accomplish the research, basic studies include a total of 19 total soundings, 5 (CPTu) soundings and 3 vane shear tests and 2 undisturbed samples with parallel test series data has been collected. Including the previous investigations all carried out 7 total soundings, 6 rotary pressure soundings and 1 (CPTu) and made four undisturbed sample series. See figure 15 for an overview of the previous investigation bore points where the data are used for this thesis work. The data of CPTu that evaluates the ground water condition, Total sounding, Liquid limit, plastic limit and water content measurements were correlated for the analyses to verify the presence of quick clay in the study area.

4.1.3 Data collection

Site investigation at different sites, with CPTu data collection, total sounding, sample analysis and pore pressure measurements by SVV(dated: 23.04.2012 *Kvikkleireskred ved Fv208 i Åby i Bamble)* was used. One must bear in mind that there might be some errors in collecting the data which might affect the interpretation of the results. Detailed location of the investigation sites is shown in figure 15.



Previous slides
Test points
CPTu and Total sounding bore points considered in the thesis

Figure 15. Locations where the data has been collected (SVV, Kvikkleiereskred ved 2008)

4.1.4 Total sounding data

A total sounding investigation was performed and data were analyzed which helps to map the stratification and locate 29 quick clay deposits. This gives the best indication for the presence of clay content. So, raw data were collected and plotted using Excel spreadsheet. The slope of the curve was analyzed for vital information for the presences of quick clay and tried to correlate with the corresponding water content, remolded and intact shear strength, plasticity index and sensitivity at specific depths.

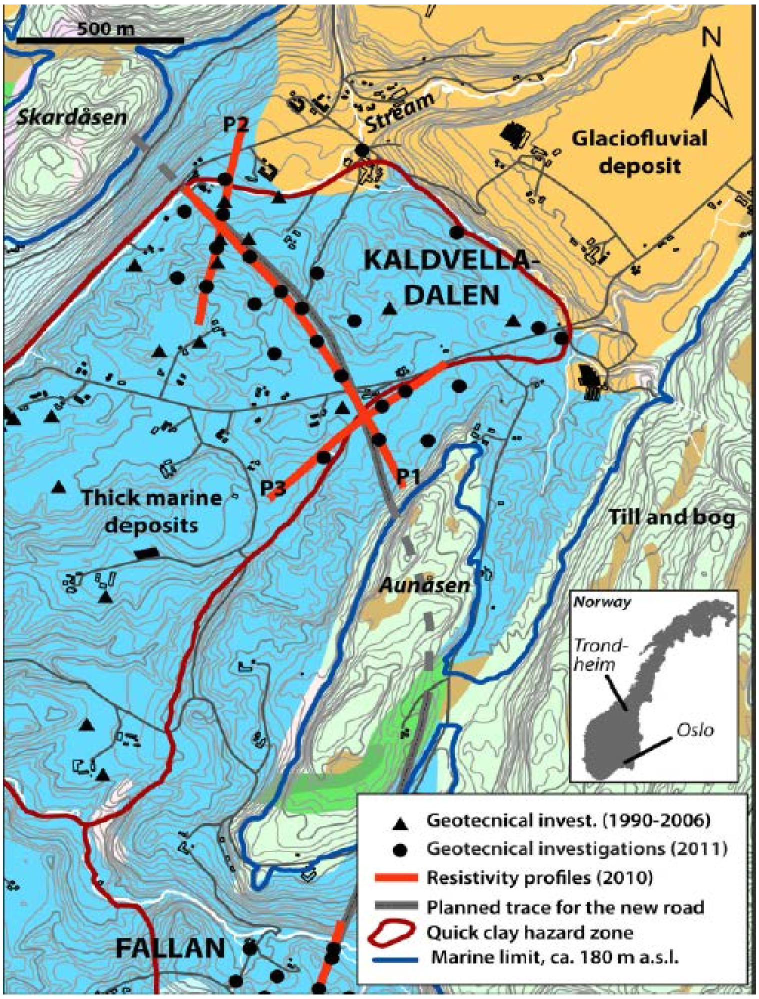
4.1.5 CPTu and total sounding Data plots and interpretation

Table 4. 1 Summary of plot interpretations

<table>
<tr><th>Site</th><th>Bore Hole no</th><th>Interpretation remarks</th><th>Reference</th></tr>
<tr><td rowspan="3">Åby</td><td>BH-1</td><td>-Linear increase in q_t and u_2 with depth
-High u_2 relative to u_0
-The lab investigation shows that there is a quick clay layer from depth 5.5m to 14.5m.
-After 15m the slop of total sounding vs depth plot is vertical and negative slop that leads a suspection of quick clay layer.
-High OCR form 0 to 5.5m</td><td>Appnedex-1 Plot 16
Appendix-2 BH no.1
Appendix-2 data calculated
(*BH=bore hole)</td></tr>
<tr><td>BH-9</td><td>-Linear increase in q_t and u_2 with depth
-High u_2 relative to u_0
-The lab investigation shows that there is a quick clay layer from depth 4.5m to 10.5m.
-After 18m the Bq>1 that leads a suspection of quick clay layer.
-High OCR form 0 to 4m</td><td>Appnedex-1 Plot 17
Appnedex-2 BH no.9
Appendix-2 data calculated</td></tr>
<tr><td>BH-10</td><td>-Linear increase in q_t and u_2 with depth
-The lab investigation shows that there is a quick clay layer from depth 4.5m to 10.5m.
-After 18m the Bq>1 that leads a suspection of quick clay layer.
-The remolded shear strength found from vane shear test is much higher than the C_{ur} from lab fall cone test.
-High OCR form 0 to 4m</td><td>Apneddex-1 Plot 18
Appnedex-2 BH no.10
Appendix-2 data calculated</td></tr>
</table>

4.2 Fallan and Kaldvelladalen site

Fallan and Kaldvelladalen are located in the municipality of Melhus, about 25 km south of Trondheim in Mid Norway (Figure. 19). The area is cultivated and is surrounded by the hills Skardåsen and Aunåsen. The terrain is undulating with elevations of 99-145 m a.s.l., and there are several traces of erosion and land sliding. The study area is located within Engan quick-clay hazard zone and according to the Quaternary geological map, the area has thick deposits of marine clay (Rolf Sandven and Inger-Lise Solberg, 2011).



Legend:

- Geotechnical investigation (1990-006)
- Geotechnical investigation (2011)
- Resistivity profiles (2010)
- Planned trace for the new road
- Quick clay hazard zone
- Marine limit ca.180m a.s.l.

Figure 16. Study area in Kaldvelladalen and Fallan with 2D resistivity profiles (Rolf Sandven and Inger-Lise Solberg, 2011)

The purpose of the investigations was to map the ground conditions and evaluate the geotechnical challenges for the new road. Both geotechnical investigations and 2D resistivity measurements on the surface were used in this investigation.

4.2.1 Data collection

According to (Rolf Sandven and Inger-Lise Solberg, 2011), 25 rotary pressure soundings (8.9-55.1 m deep), 8 CPTu measurements (30.0-40.0)m deep and undisturbed 54 mm piston samples at 5 locations (depth intervals: 2.0-21.8 m) are taken.
In this study, the selected points for analysis are listed in table 3.1

Table 4. 2 Data point selected for analysis

Site	CPTu No.	Rotary sounding No.	Lab. BP-No(Bore hole no)
Kaldevalldalen	109 and 118	109 and 118	109 and 118
Falan	1,2,5,7	1,2,5,7	1,2

4.2.2 CPTu and Rotary sounding data plots and interpretations

Table 4.3 Summary of plot interpretations

Site	Bore Hole no	Interpretation remarks	Reference
Fallan	BH-1	-High u_2 relative to u_0 -The lab investigation shows no quick clay layer,but from rotary sounding plot,4m-10m the slop of the curve is vertical that shows quick clay behaviour. -High OCR form 0 to 4m	Apneddex-1 Plot 19 Appnedex-2 BH no.1 Appendix-2 data calculated
	BH-2	-The lab investigation shows no quick clay layer,but from rotary sounding plot,4m-8m,15-20m and 22-24m shows the slop of the curve is vertical that shows quick clay behaviour. -High OCR form 0 to 8m -Lab data fromBP-1 is used due to proximity of the points where the sample taken.	Apneddex-1 Plot 20 Appnedex-2 BH no.1 Appendix-2 data calculated
Kaldvelladal -en	BH-118	-The lab investigation shows no quick clay layer. Rotary sounding plotshows , 2m-3m and 7m-17m the slop of the curve is vertical that implies quick clay behaviour. -High OCR form 0 to 4m -Lab fall cane test shows no quick clay layer.	Apneddex-1 Plot 22 Appnedex-2 BH no.118 Appendix-2 data calculated

4.2.3 Comparison with 2D resistivity results

The data from geotechnical soundings are plotted side by side with the laboratory test data for the identification of the quick clay layer. After the interpretation of the graphs from the slop of the tip resistance and the basic criteria's of quick clay identification i.e., remolded shear strength, $Cr \leq 0.5$, water content, $w > _{wl}$, liquid index $I_l > 1$ $_{wl}$, pore pressure ratio Bq>1 ,the result was also compared with the available 2D resistivity profiles as shown on figure 23.

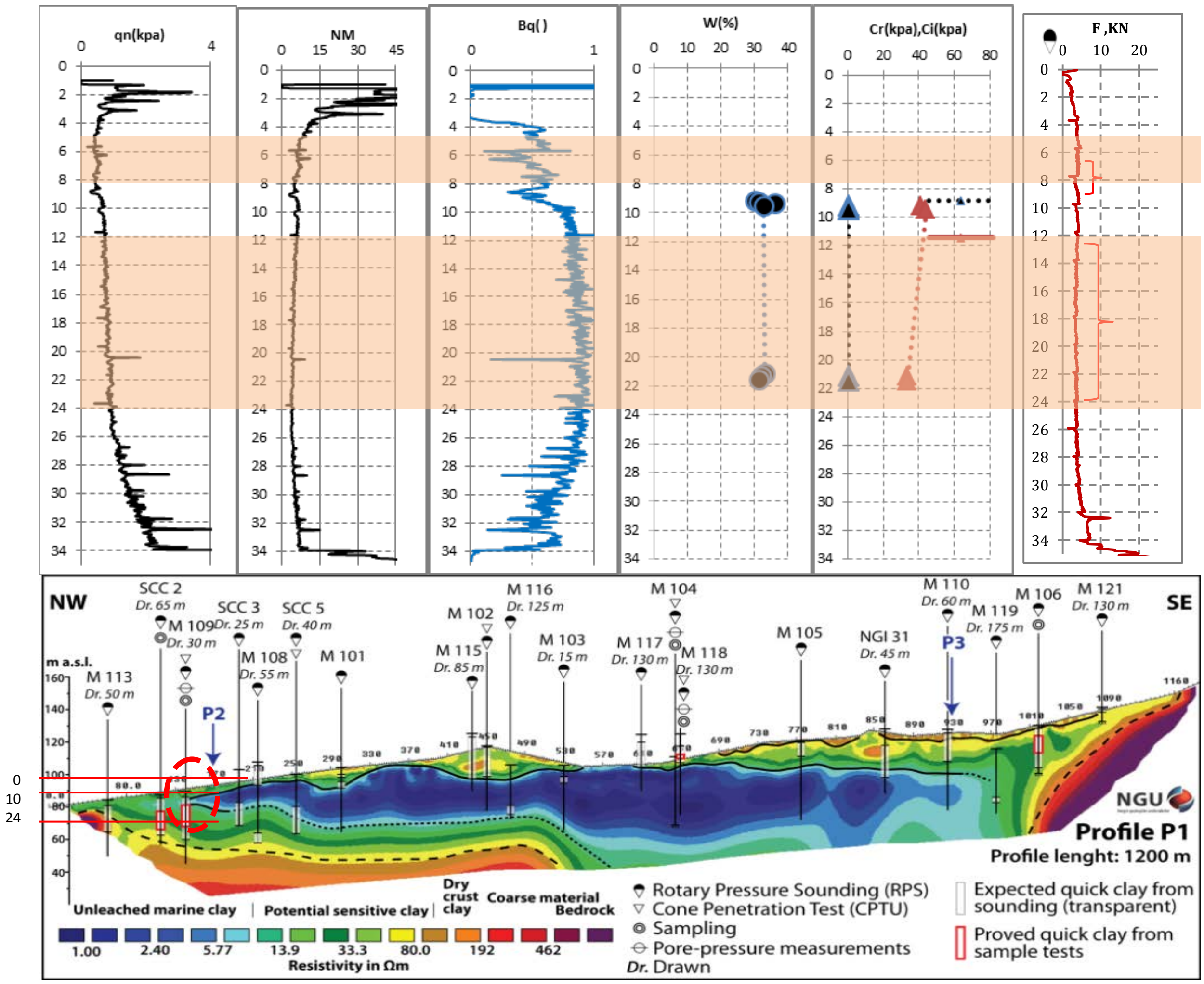


Figure 17. Electrical resistivity plots compared with the sounding results

From the resistive plot, from 10m depth down to 25m, quick clay layer is expected and proved from lab report.

Kaldvelladalen (106)

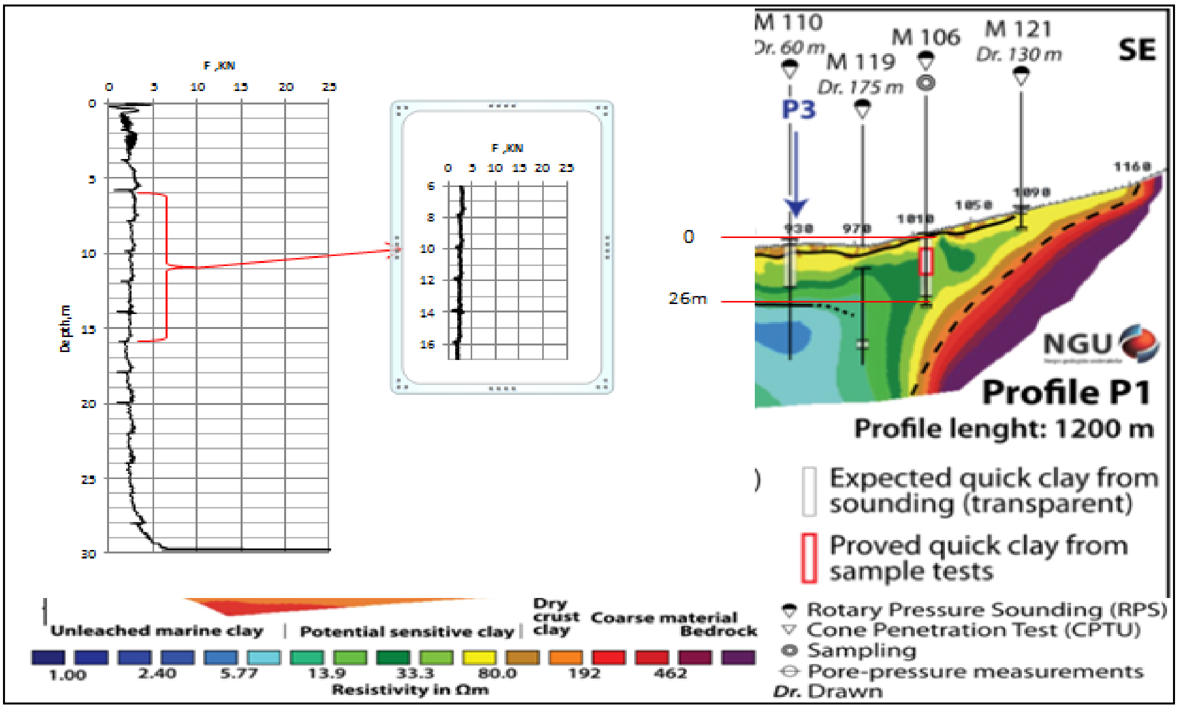


Figure 18. Electrical resistivity plots compared with the sounding results

Only rotary sounding data is plotted and compare with the resistivity plots. At 10m from the top, quick clay is found from the lab report and quick clay layer is expected from 2m to 18m depth, and this lab result conformation of quick clay is much with the resistivity result. The slop of the rotary sounding tip resistance vs. depth shows a possible quick clay layer from 6m-16m depth which also matches the resistivity plots of possible sensitive clay zone.

4.3 Byneset Site

Byneset is located in western Trondheim. Quick clay slide was happened which has a size about 150 m wide and 450 m long. Avalanche had an outlet approx. 870 m landslide location stated in the overview map.(see appendix). According to the NGU hazard mapping, the area is categorized at risk class no.3. See figure 26.

Figure 19. Byneste quick clay slide location based on risk mapping (www.NGU.no)

4.3.1 Data collection

In this site, it is performed one CPTu, 2 groundwater measurements, pore pressure measurements at two drill points, and 32 sampling (54 mm and 76 mm steel cylinder samples) in the drill point 2, 11, 12, 13 . For this study, data from Borehole no. 11 and 12 are considered and interpreted.

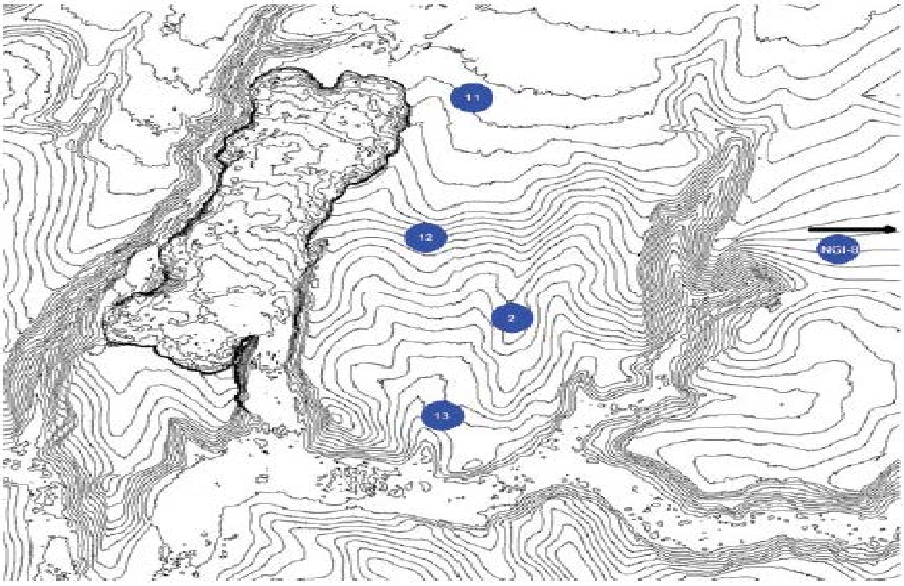


Figure 20. Laser scanning slides pit and a list of tentative placement of bore holes (NIFS)

4.3.2 CPTu and laboratory data plots and interpretations

Table 4. 4 Summary of plot interpretations

Site	Bore Hole no	Interpretation remarks	Reference
Byneset	BH-11	-The lab investigation shows no quick clay layer,but high Bq value is shown on the plot -The resistivity plot shows leached layer, which is >15Ω from 2-18m depth -Brittle caly property is shown from 4.5m - 5.3m from the lab report.(0.5kpa<Cr<2kpa)	Apneddex-1 Plot 23 Appnedex-2 BH no.11 Appendix-2 data calculated
	BH-12	-The lab investigation shows quick clay from 10-12.5m -High OCR value from 2-6m shows no quick clay layer is expected within this layer. -Quick clay layer is located even though there - -Bq value is very low. -Brittle clay at 4.6m indicated from lab report.(0.5kpa<Cr<2kpa)	Apneddex-1 Plot 24 Appnedex-2 BH no.12 Appendix-2 data calculated

4.4 Tiller

Due to the thickness and uniformity of the clay deposit, its high sensitivity and its proximity to the city of Trondheim, the Tiller site has been used for research purposes by the Norwegian NTNU since 1980's. The site is sometimes referred to as Kvenild (after the neighbouring farm) and it is located 15km southern of Trondheim,Sør-Trøndelag.

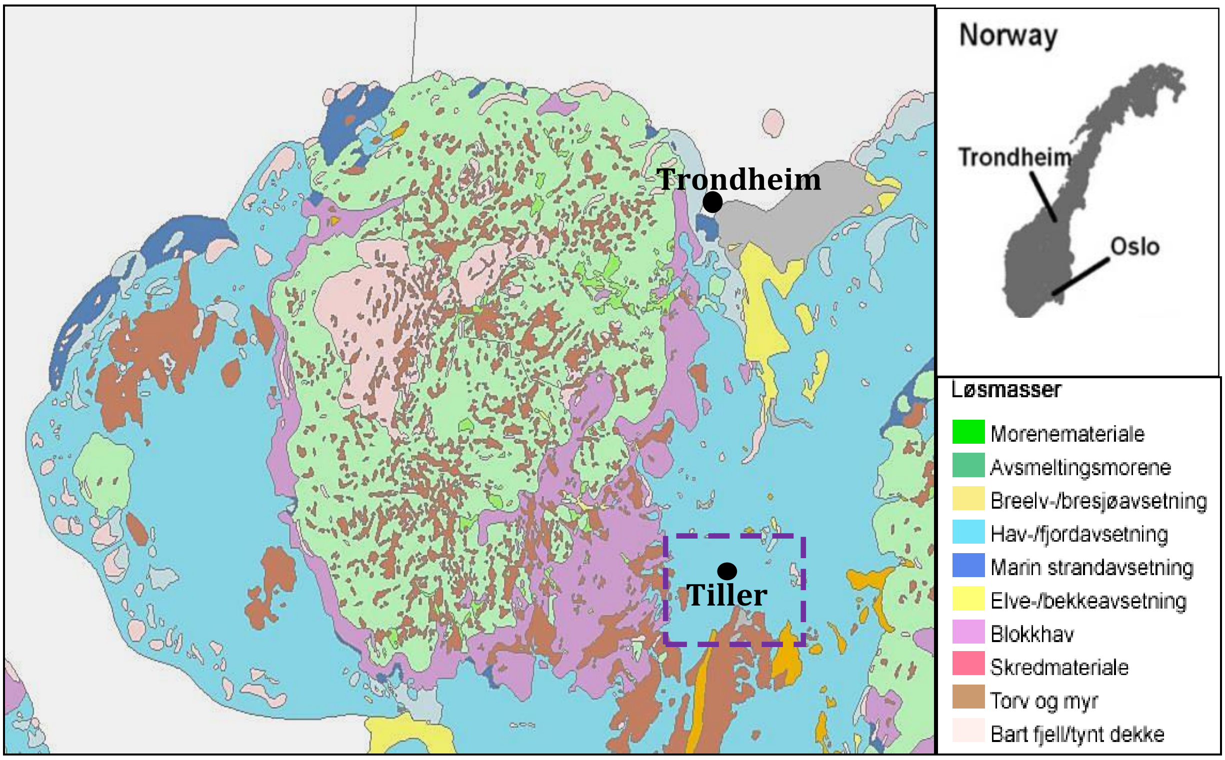


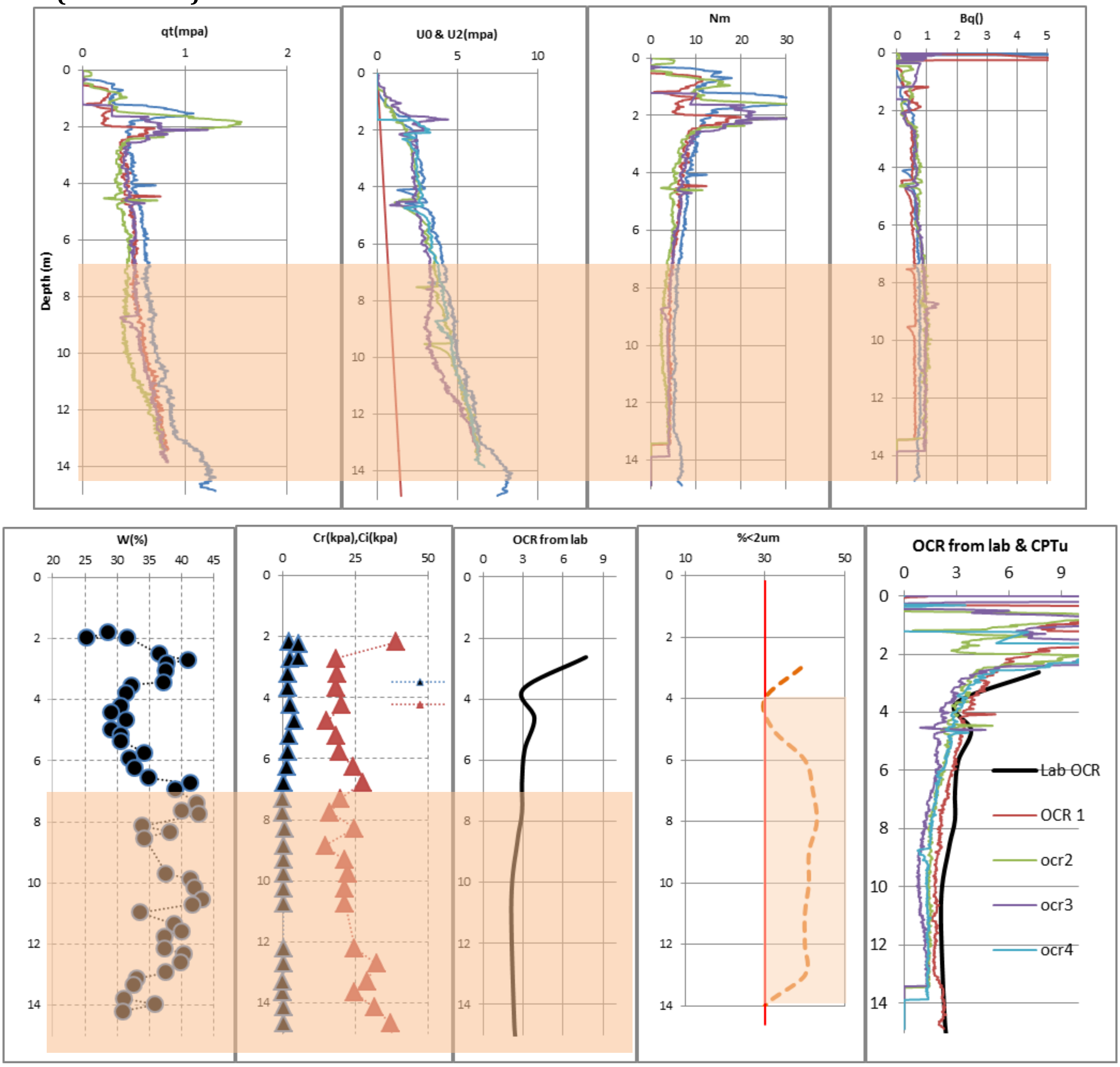
Figure 21. Quaternary map of soil deposits in Sør-Teøndlag area (www.NGU.no)

4.4.1 Data collection

Four CPTu investigations have been made with a laboratory investigation which was made by the Division of Geotechnical Engineering and SINTEF in 1989.
Due to the proximity of the four CPTu points and the lab sample point, the available lab report is used for the interpretation of the four CPTu plots.

4.4.2 CPTu and lab data plots and interpretations

Tiller(BH-1-2-3-4)



Remarks

- The lab investigation shows quick clay layer from 7m -17m
- High OCR value from 2-4.5m, and the OCR value found from the lab report and from the CPTu(calculcated) has similarities.
- The percentage of clay content <2um is >30% from 4m -14m depth shows a layer of quick clay within this depth.

Figure 22. Data plots and interpretation

4.5 E6-Harran

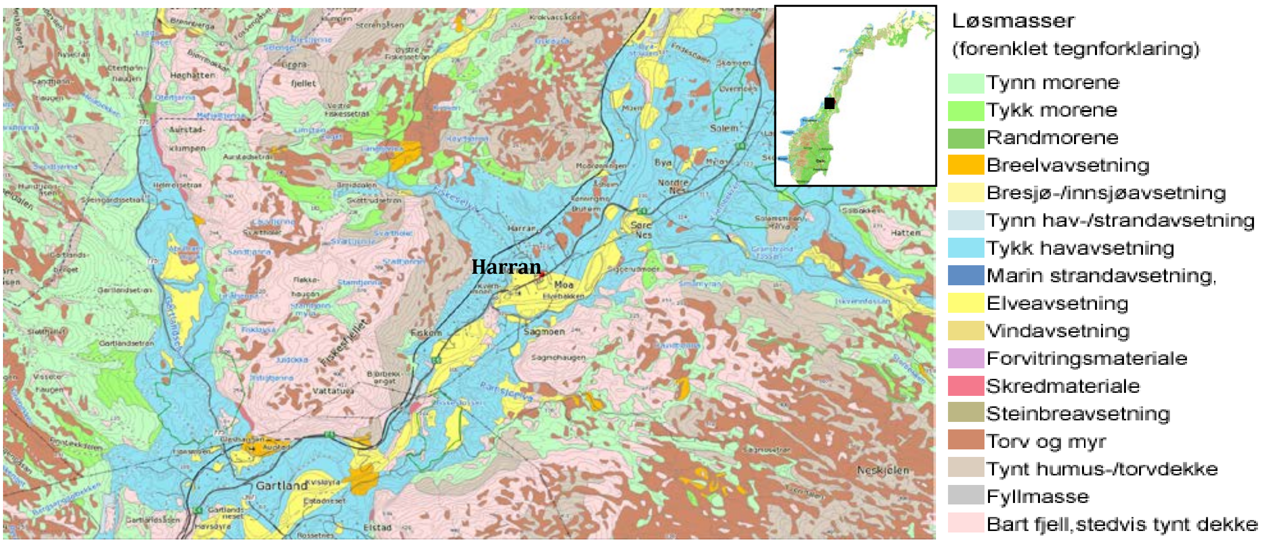


Figure 23. Quaternary map of soil deposits in the Harran area (www.NGU.no)

4.5.1 Data collection

A joint geotechnical investigation was made by Multiconsult and Staten vegvesen for the road project of E6-Harran. Even though many CPTu, rotary soundings and laboratory investigations have been made along the root where the road is to be built, for this thesis, the most relevant bore-hole points that fulfills the three basic investigations, i.e. CPTu, rotary sounding and the corresponding laboratory test results were considered for the correlation and identification of the quick clay layer.

4.5.2 CPTu and lab data plots and interpretations

Table 4. 5 Summary of plot interpretations

Site	Bore Hole no	Interpretation remarks	Reference
Harran	BH-9	-The lab investigation shows quick clay layer from 19m -22.5m ,Cr=0.17kpa -High OCR value from 2-6m, and the OCR value a the location of quick clay is <2 -Bq value is <1 at the quick clay layer -Slop of rotary sounding versus depth plot is vertical at the confirmed quick clay layer	Appnedex-1 Plot 25 Appnedex-2 BH no.9
	BH-15	-The lab investigation shows brittle clay layer from 12m -16.5m ,Cr=0.77kpa -High OCR value from 7-9m, and the OCR value a the location of quick clay is <2 -Bq value is slightly >1 at the quick clay layer -Slop of rotary sounding versus depth plot is vertical at the confirmed quick clay layer	Apneddex-1 Plot 26 Appnedex-2 BH no.15
	BH-16	-The lab investigation shows brittle clay layer from 22m -22.5m ,Cr=0.87kpa -High OCR value from 2-6m, and the OCR value a the location of quick clay is <2 -Bq value is slightly >1 at the quick clay layer -Slop of rotary sounding versus depth plot is vertical at the confirmed quick clay layer -Thin layer of brittle or quick clay layer may be important for slop stability assessment around the area.	Apneddex-1 Plot 27 Appnedex-2 BH no.16

Table 4. 6 Summary of plot interpretations

Site	Bore Hole no	Interpretation remarks	Reference
Harran	BH-29	-The lab investigation shows no quick or brittle clay layer -OCR value of >2 through out the investigated depth -Bq value is <1 -Slop of rotary sounding versus depth plot is increasing	Apneddex-1 Plot 28 Appnedex-2 BH no.29
	BH-35	-The lab investigation shows no quick or brittle clay layer -OCR value of >2 through out the investigated depth and hight from 2-6m -Bq value is <1 -Slop of rotary sounding versus depth plot shows vertical slop at depth from 10m-12m which could be the suspected quick clay layer location even though the lab investigation shows no quick or brittle clay layer	Apneddex-1 Plot 29
	BH-38	-The lab investigation shows quick clay layer from 7.5m -9.5m i.e., $0.1 \leq Cr \leq 1.86$kpa -Brittle clay form 13.5-14m, Cr= 2.16kpa and high OCR value from 2-6m -Bq value is <1 at the quick clay layer location -Slop of rotary sounding versus depth plot is vertical at the confirmed quick clay layer and the slop is increasing at the thin layer of brittle clay location -Quick clay expected form 6m-16m depth from the slop of the sounding plot	Apneddex-1 Plot 30 Appnedex-2 BH no.35

Table 4. 7 Summary of plot interpretations

Site	Bore Hole no	Interpretation remarks	Reference
Harran	BH-45	-The lab investigation covers from 2.5m-14.5m and shows no quick or brittle clay layer. -OCR value of >2 from 6-10m depth getting lower from depth 36m -High Bq value from depth 26m. -Slop of rotary sounding versus depth plot is almost vertical from 6-8.5m and from -26-32 m depth which could be the quick clay layer.	Apneddex-1 Plot 31 Appnedex-2 BH no.38
	BH-47	- The laboratory investigation shows a layers of quick and brittle clay layer in between 0.15kpa ≤ Cr ≤ 1.95kpa from 8m-22m. -Bq value is <1 at the quick clay layer location -Slop of rotary sounding versus depth plot is vertical at the confirmed quick clay layer and quick clay expected form 22-24m depth from the slop of the sounding plot	Apneddex-1 Plot 45 Appnedex-2 BH no.45
	BH-53	-The lab investigation shows brittle clay layer from 21m -22m , Cr < 2kpa -High OCR value from4-12m, and the OCR value a the location of quick clay is <2 -Bq value is slightly >1 at the quick clay layer -Slop of rotary sounding versus depth plot is vertical with some pick resistances and vertical slop from 12-14.5m and from 22m downwards	Apneddex-1 Plot 33 Appnedex-2 BH no.47

4.6 Additional interpretation from E39 road project

Data from this site was collected just to show how the sounding data interpretations sometimes completely different from the actual laboratory investigations. The data were collected from the undergoing project at the south-east of Trondheim. (See appendix for the location and bore plan).

For this project, a total of 6 soundings including laboratory investigation were undertaken. However, only two points, i.e. CPTu-3, CPTu-5 with the corresponding total sounding and laboratory investigations were plotted and interpreted. In addition, the rest of the investigation points were also presented for discussion.

4.6.1 Plots and interpretations (BH-3)

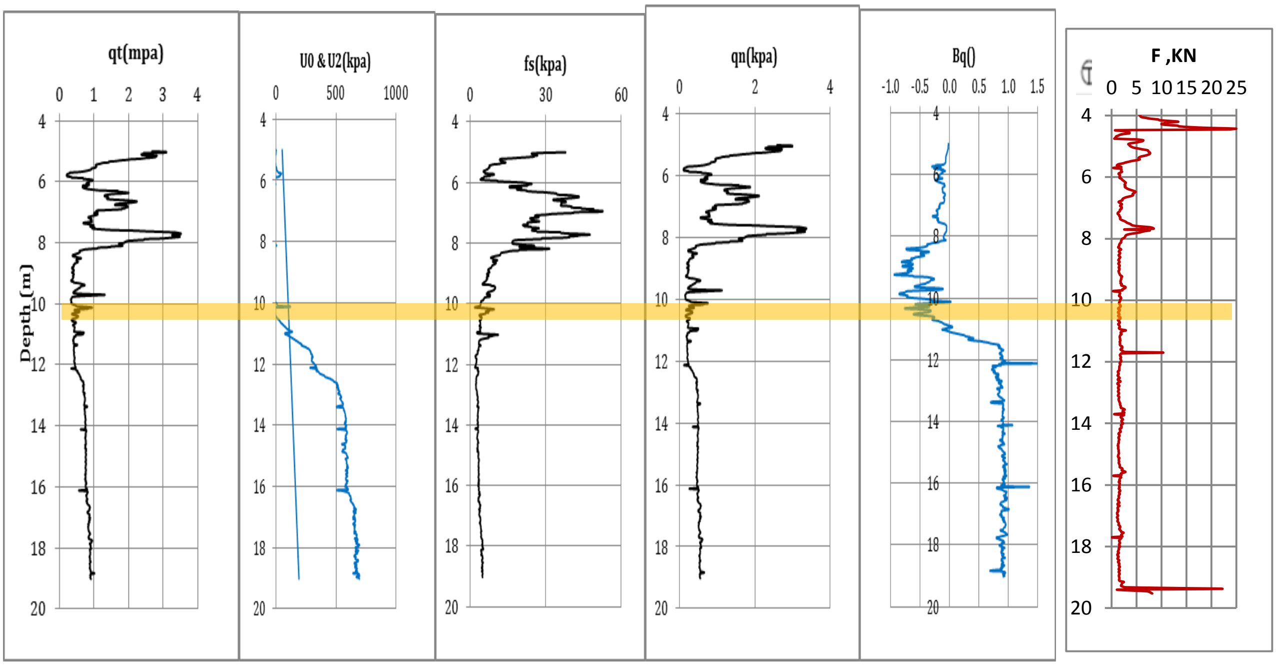


Figure 24 Data plots and interpretation

The above plots and interpretation shows that, even though the laboratory investigation confirms a quick clay layer of only 50cm, which is from depth 10m-10.50m (the yellow highlighted), all the rest layers are silty and sand mixed material. The total sounding plot implies a vertical slop from 8m down to 19m which is the implication of the quick clay layer. This is a good implication that how depending only on the interpretation of sounding data are misleading unless otherwise more research and study should be done to relay on. (Refer the appendixes for the rest of the plots and laboratory investigation reports).

4.6.2 Plots and interpretations (BH-5)

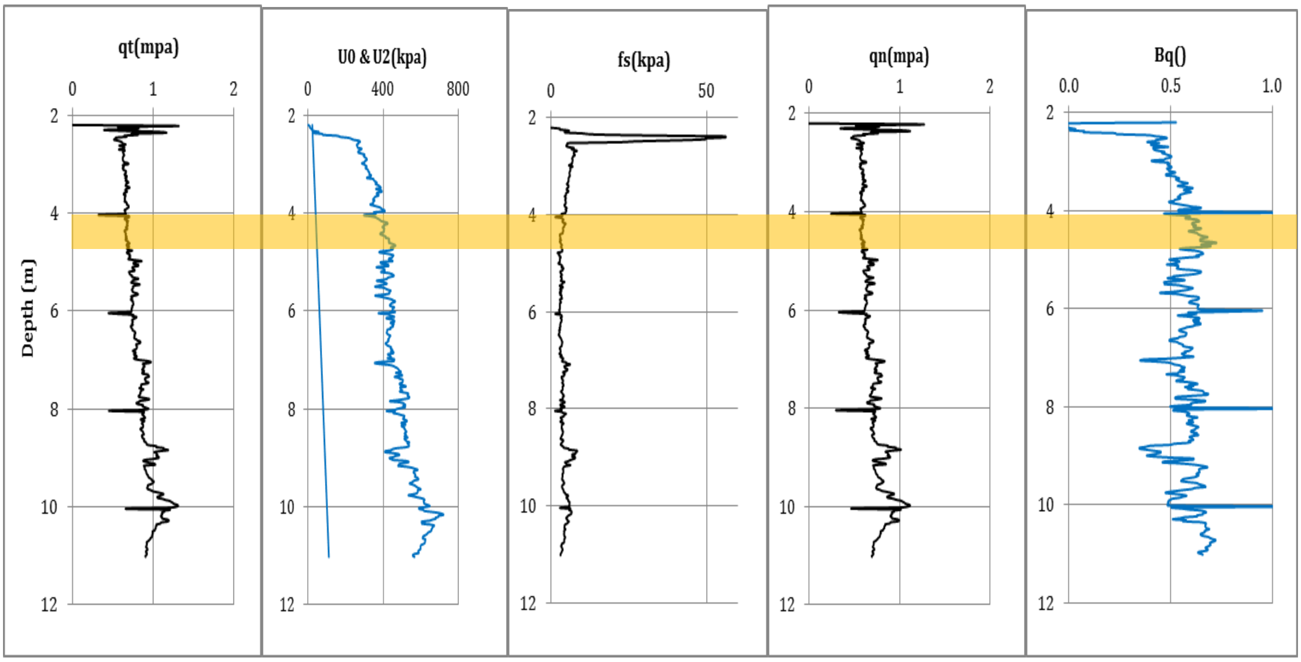


Figure 25 Data plots and interpretation

The above plots are also shows that quick clay layer is confirmed from the depth of 4m-4-5m even though vertical slops are shown on the 'q_n' and very low sleeve friction were recorded. The grain size distribution (see appendix), implies quick clay as the same depth where the quick clay layer was confirmed. Table 4.2 shows a remolded shear strength of <0.5kpa which is the zone of quick clay layer with a very high sensitivity.

Table 4. 8 Laboratory test result (Extracted from plots)

w(%)		**Remolded**		**Intact**		**S_t**
W(%)	**Depth(m)**	**Cr(kpa)**	**Depth(m)**	**Ci(kpa)**	**Depth(m)**	
37.91	4.15	0.42	4.24	69.38	4.24	165.20
33.18	4.36	0.31	4.54	55.17	4.54	177.95
36.97	4.45					
34.60	4.65					

4.7 Plots of B_q versus N_m

Pore pressure ratio, B_q versus cone resistance number, N_m plotted to see how related they are and to analyze the trend of each site with this parameters. See figure 42 .

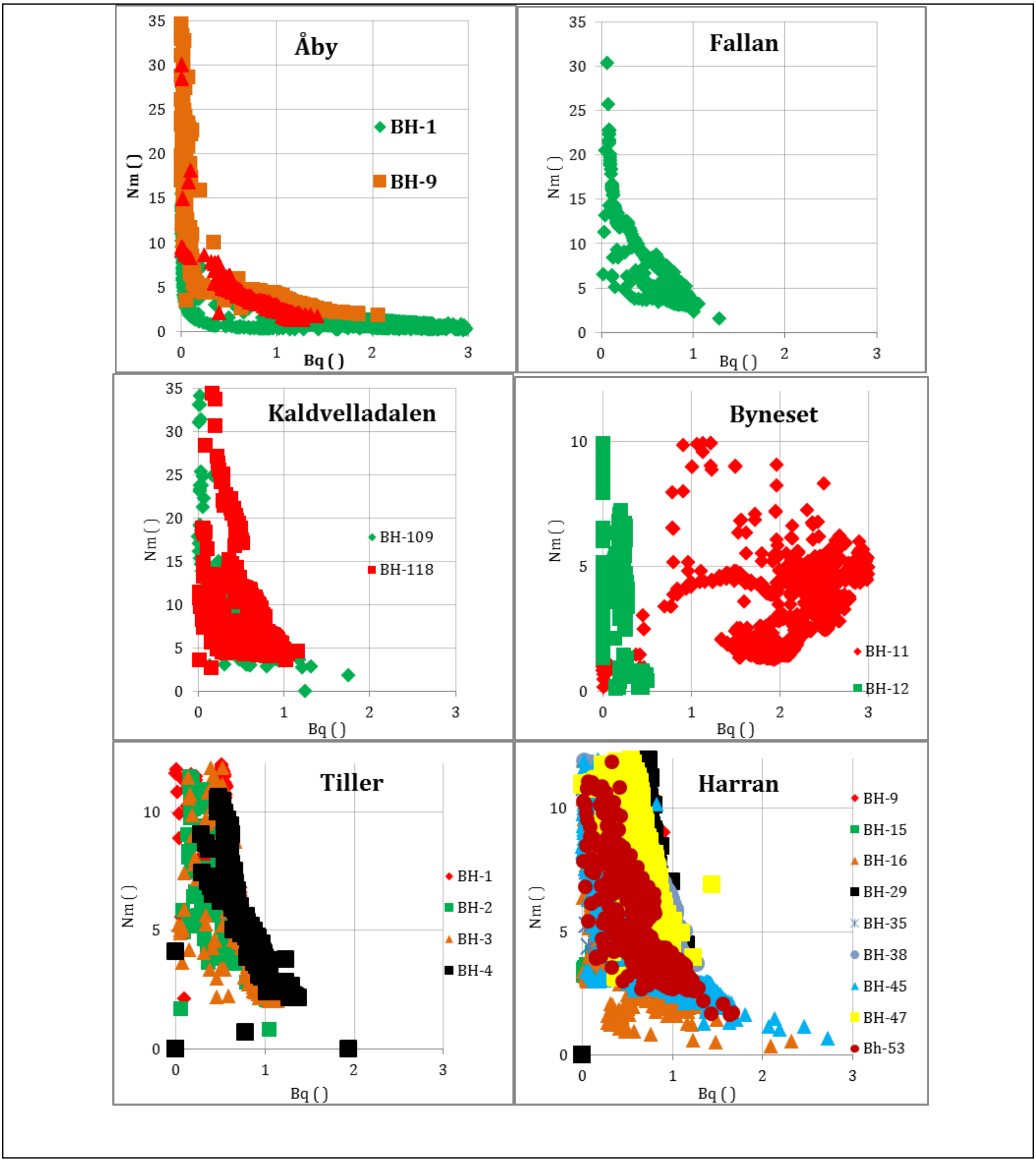


Figure 26. Pore pressure ratios, Bq, versus cone resistance number, Nm, plots for all sites

In all sites, except Byneset, the Bq versus Nm graph shows that as Bq value increases the Nm values decrease. Even though analyzing more data are required, we can understand from this plot is that how the cone resistance is influenced by the increasing or decreasing of the Bq value which is the ratio of the change in pore pressure and the net cone resistance, q_n.

4.8 Plots of Bq versus OCR

Pore pressure ratio, Bq versus over consolidation ratio, OCR, was also plotted just to see how related they are and analyze the trend of each site with this parameters. See figure 43.

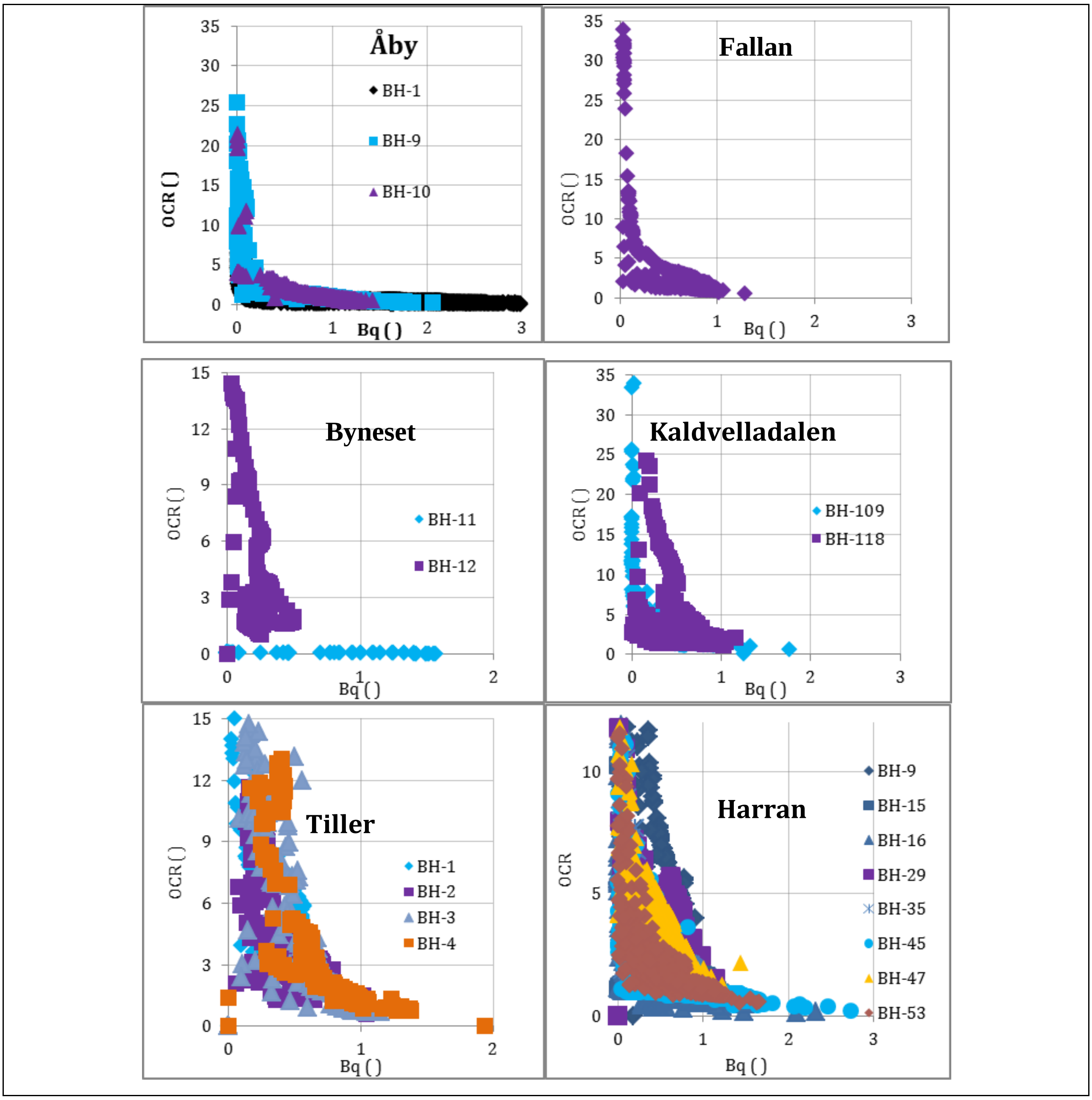


Figure 27. Pore pressure ratios, Bq, overconsolidation ratio, OCR, plots for all sites

Pore pressure ratio, Bq, versus OCR plot shows that pore pressure ratio decrease when the overconsolidation ratio increase for all the selected sites where the data are taken.

4.9 Soil classification using Robertson & Campanella charts

For the general classification of the soil, the data are also plotted under Robertson & Campanella chart just to see how this method is working and how much it coincides with the results found so far using the interpretation of the plots. Even though most of the points are in the zone of clay, which is zone-2, no quick clay or highly sensitive clay is located which is unlike the other interpretation and laboratory results which conform quick clay layers. See figure 44.

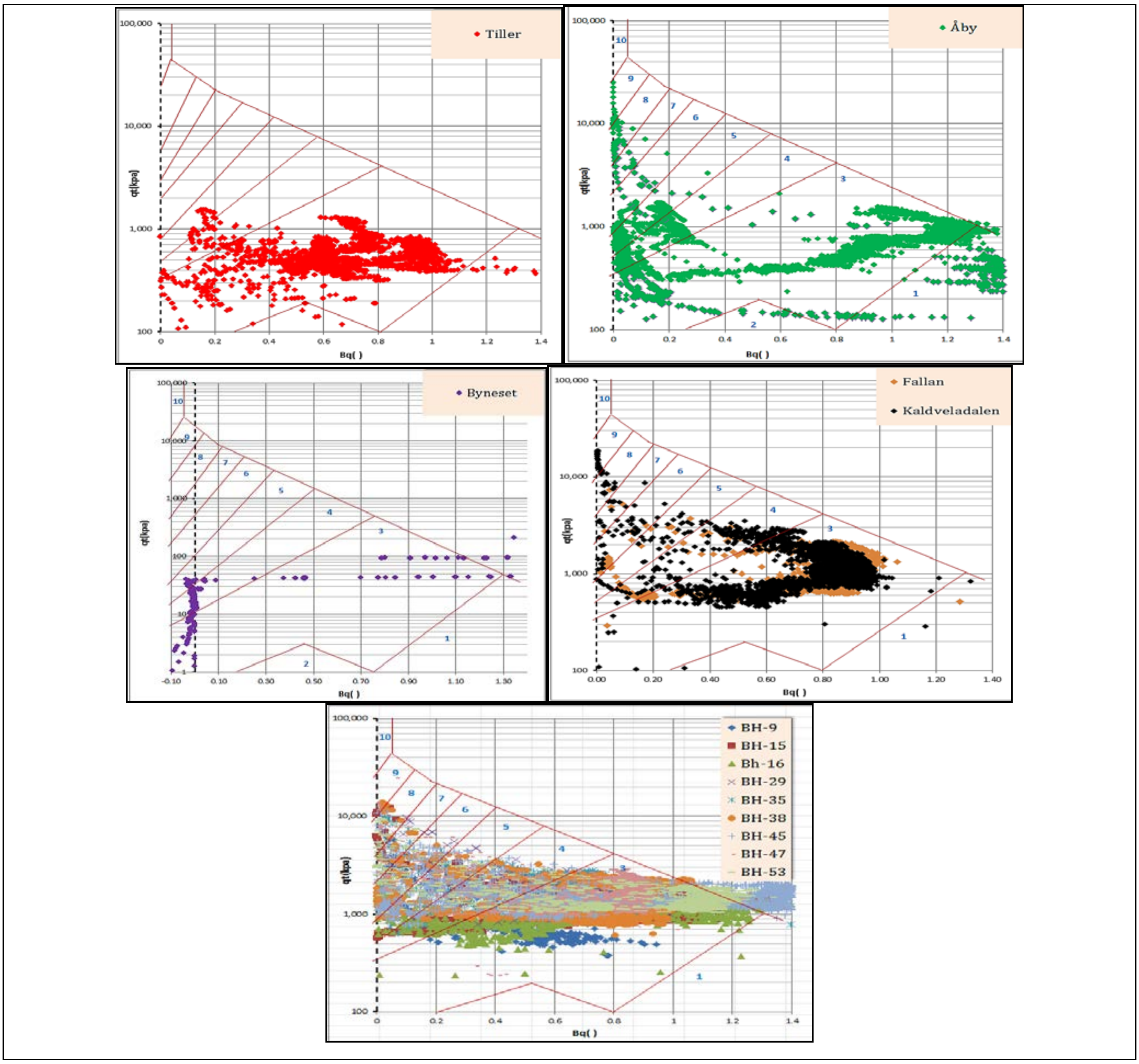


Figure 28. Data plots on the Robertson & Campanella chart

5. Discussions

In this thesis, basically special emphasis has been put on interpretation of the plots from CPTu, Rotary sounding, Total sounding and the results from laboratory tests on samples for the location and identification of quick clay. The correlation between the slop of the tip resistance versus depth curve and the identification of the quick clay layer based on the inclination from vertical was also analyzed.

Numerous quick clay identification methods are reported to locate the quick clay layer from CPTu, rotary or total sounding data and electrical resistivity test results. However, their validity still needs to be verified by laboratory test results. The present interpretation analysis shows that the CPTu identification methods are capable of interpreting the subsurface soil type with a good accuracy and these results compare well with the laboratory test results.
The study has shown that there is a general correlation between the slope of the pushing force to depth curve and the sensitivity or quickness of the soil at the same depth. However, since there is no direct connection between pushing force and sensitivity, there is a large variation in sensitivity for any given slope of the sounding curves, except for the very flattest.

For quick clay consideration: Bq>1, w>wl, S_t>50, C_r<0.5, I_l>1 and for data without lab report, B_q>1 and slop inclination is considered for the interpretation of the plots. However, due to the insufficient amount of laboratory data, it was very difficult to match the plot results and to decide if the sounding plots are giving a true picture of the location of the soil in the subject. However, in most cases, the suspected quick clay location from the rotary or total sounding versus depth plots fits with the laboratory results of the same point, which is a good implication of how the sounding methods are reliable if it is supported by a limited amount of sample investigation.

At some test sites, example Åby, a very high rod inclination was registered which could incur an additional vertical resistance which misleads and distort the actual values that can change the plots pictures .Therefore, the amount of road inclination should be given a good attention before the interpretation of the plots.

Even though a very limited amount of resistivity data was available, some comparisons were made at Kaldvelladalen site and at 10m from the top, quick clay is confirmed from the lab report and the resistivity result confirmed that too.

The slop of the rotary sounding tip resistance vs. depth shows a possible quick clay layer from 6m-16m depth which matches the resistivity plots of possible sensitive clay zone. This generally shows that due to the large area coverage of the resistivity testes, it could be a good start to compare the results of sounding investigation with the resistivity tests to see how much they coincides each other.

On Tiller site, four CPTu data are found and compared with one lab data available. The lab test shows more brittle clay than quick clay, even though there are some quick clay layers with low Cr in between. The particles size analysis shows a quick clay layer from 4m to 14m depth and the OCR value found from lab almost matched with the one calculated from qt-elevation values, which is a good implication of the calculated OCR from CPTu data can have a good resemblance with the laboratory results.

Robertson and Campanella soil classification chart was also used just to see the general trend to which zone the soil is belong to. According to their charts, most of the layers in Fallan, Kaldvelladalen, Tiller and Åby sites are in clay zone and very few sensitive layers are shown in Åby and very few in the rest of the sites. Byneset site shows more of silty clay to clay zone, no sensitive fine grained in this area, according to the chart. Therefore, this classification is unlike the one we found from the laboratory tests made on each site which conforms there is a quick clay layer on almost every points. Therefore, it will not be wise to relay on this classification unless otherwise it is supported by other investigation methods.

Correlations between parameters interpreted from CPTu and laboratory test results generally require good sample quality. Experiences show that CPTu is a very good method to provide reliable soil parameters and good interpretations, particularly if local correlations between high quality laboratory tests and CPTu data can be made.

When rotary and total sounding investigation methods are compared to the CPTu, It is well understand that the CPTu is an excellent tool for the geotechnical investigation in developing a site profile as it helps to record additional parameters, like pore water pressure which helps to calculate Bq, sleeve friction which can be retrieved directly from the raw data. However, when the CPTu is used to govern the depths from which soil samples are recovered for detailed laboratory study, fewer sample levels are needed, thus reducing the costs of a site investigation while simultaneously increasing the quality of the information because important layer information and layer boundaries are not overlooked.

When the particle size of a soil penetrated becomes a significant fraction of the cone diameter, and then qc can increase abruptly because of the decreased compressibility due to having to displace these particles as rigid units, which tends to produce sharp peaks in the qt versus depth plots.

It should be observed that the variations in total penetration force are not related to rod friction alone, but significant changes in tip resistance may distort the general picture. Thus, the large change in tip resistance after passing through the stiffest part of the dry crust makes it difficult to come up to a conclusions about the sensitivity in the layer just below the crust.
The overconsolidation ratio OCR was determined on the basis of qt, σ_{vo}, σ'_{vo} and a coefficient 'a' which is related to plasticity index. OCR which is calculated based on the parameters mentioned before gave very large and scattered values. As a result it was used just for comparison. OCR based on a laboratory oedometer test data from Tilller site shows a good much with the calculated OCR value from the CPTu results of the same site. This clearly indicates that the reliability of qt-elevation based OCR if it is supported by the laboratory oedometer test results.

6. Recommendation of further work

- The key for successful quick clay delineation is to integrate the classification from CPTu, rotary pressure sounding, total sounding, vane shear testing and laboratory tests providing point information with the surface geophysical sections of physical material properties which can then be classified as clay, brittle clay and quick clay.
- Electrical resistivity is a suitable indicator for quick clay if calibrated to the conventional site investigation made so fare i.e. all the soundings and laboratory tests.
- To come up to the best interpretation results on the identification of quick clay layers, a very significant amount of data from site and full depth laboratory investigation results which is directly related to the point where the investigation has taken should be analyzed and correlated. Then, it could be a good start to have a reliable interpretation results from the plots of the soundings for the precise identification of the quick clay layer without the help of any laboratory test results.
- Electrical resistivity can be used for separation of leached soil volumes in marine clays that may contain quick clay. The technique may thus be used as a screening tool in order to delimit areas where further investigations are needed from areas that do not require more attention.

- From the rotary sounding versus depth plots, some depths were identified as a layer for quick clay form the inclination of the curve, however, these should be checked with the laboratory results so that the plots form this sounding methods could be a reliable identification method in the future.

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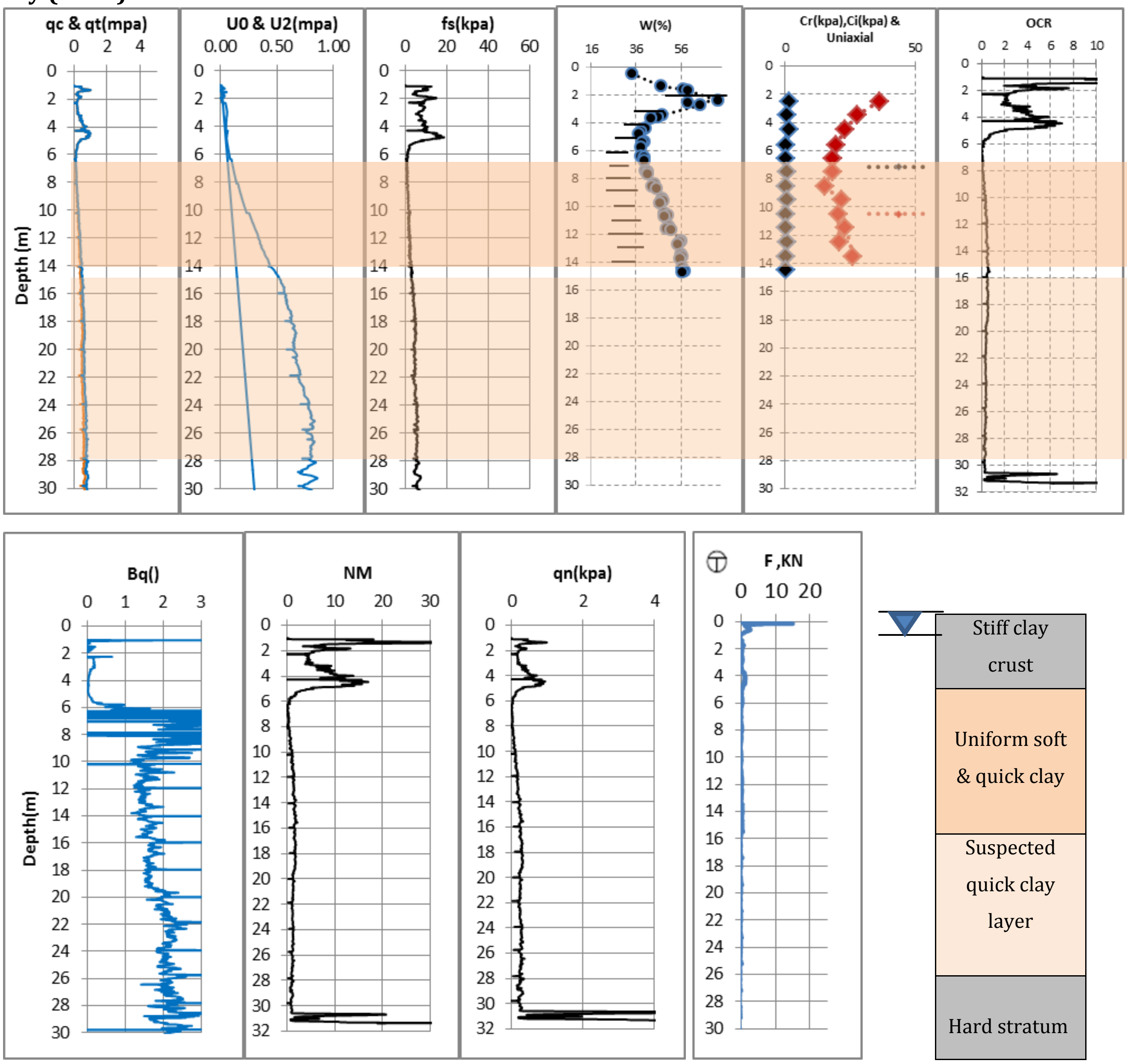
APPENDICES

Appendix 1 - Data plots

Åby (BH-1)

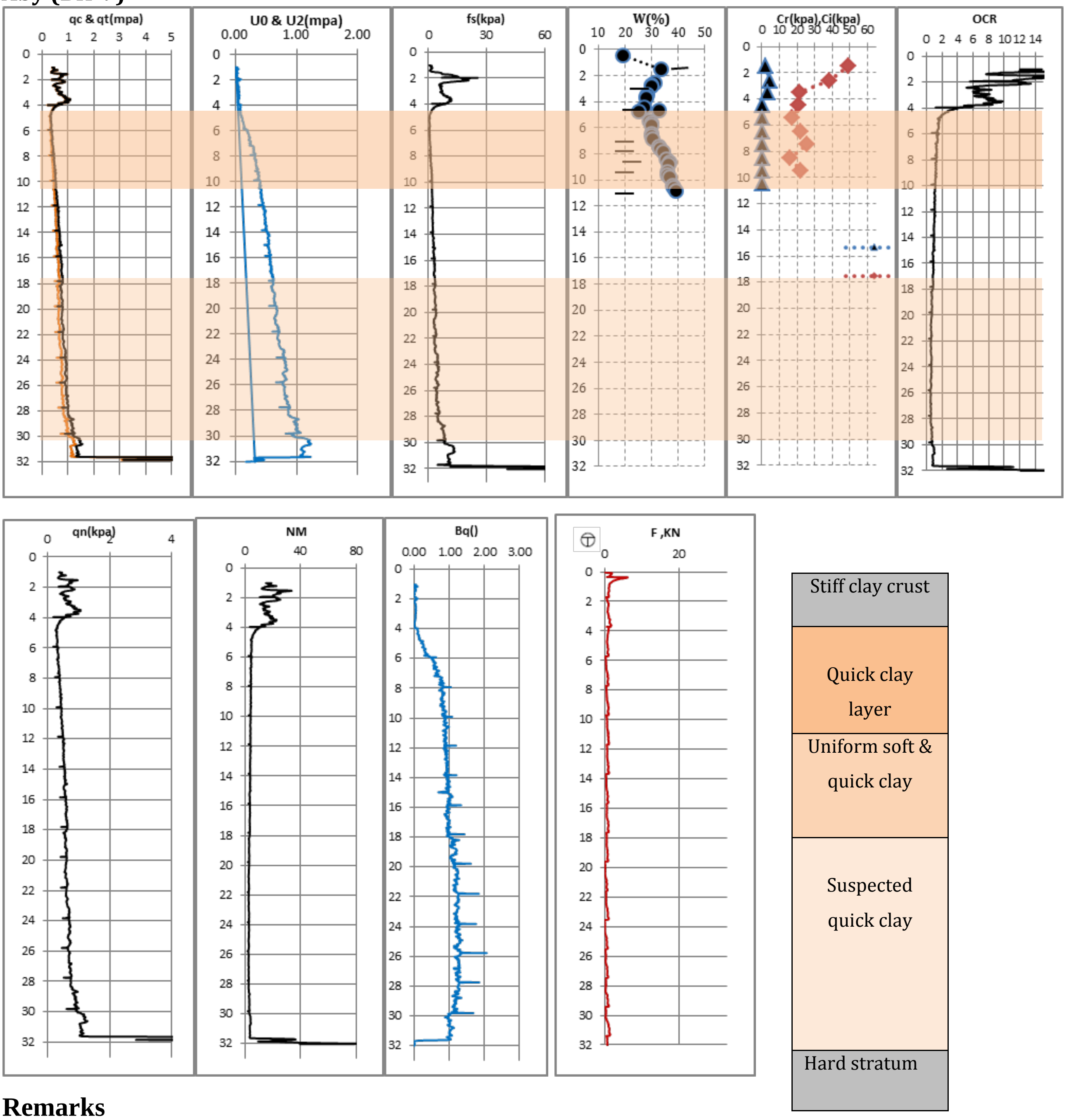


Remarks

- Linear increase in q_t and u_2 with depth
- High u_2 relative to u_0
- The lab investigation shows that there is a quick clay layer from depth 5.5m to 14.5m.
- After 15m the slop of total sounding vs depth plot is vertical and negative slop that leads a suspection of quick clay layer. High OCR form 0 to 5.5m

Plot 16. Åby data plots and interpretations

Åby (BH-9)

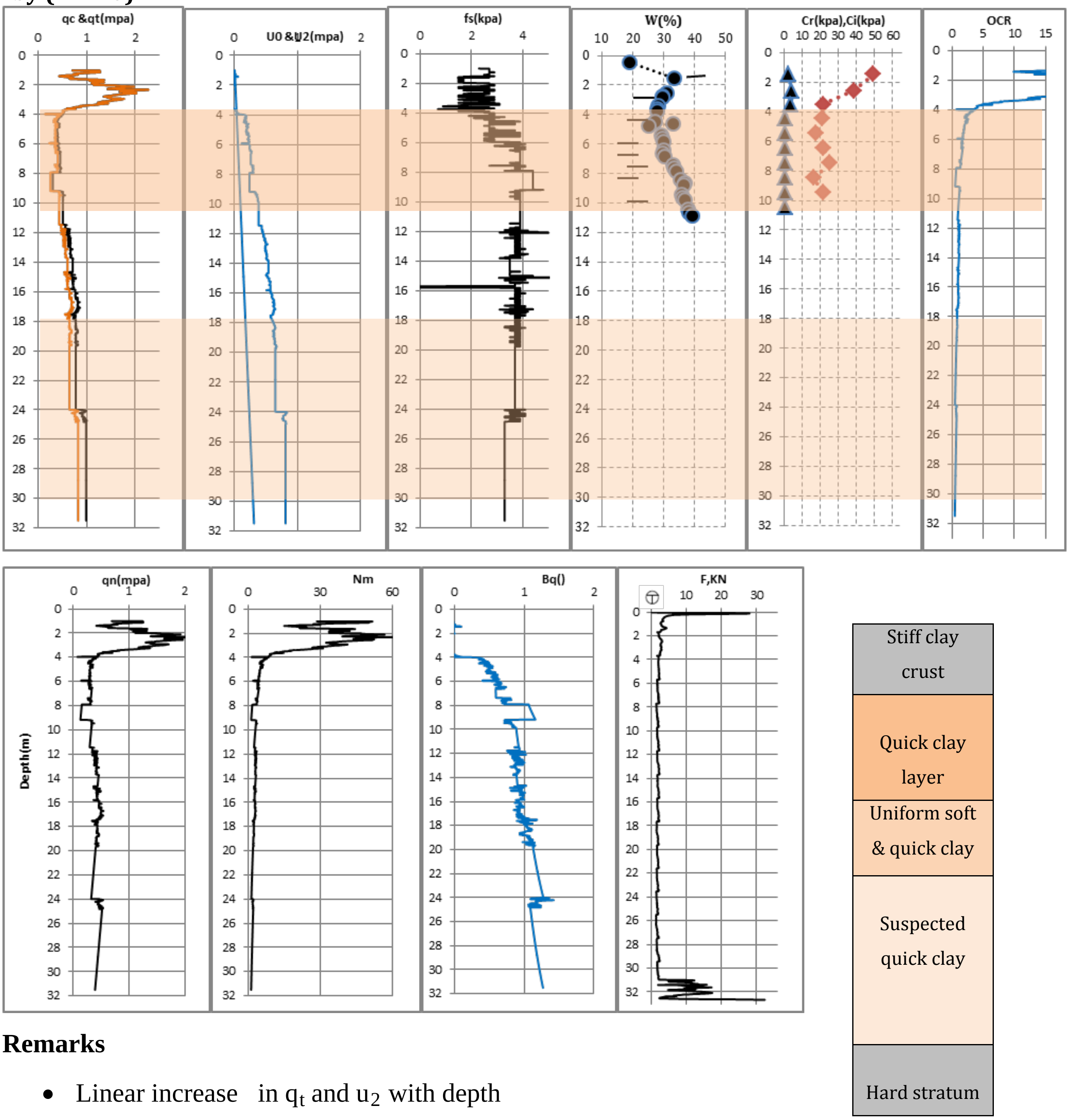


Remarks

- Linear increase in q_t and u_2 with depth
- High u_2 relative to u_0
- The lab investigation shows that there is a quick clay layer from depth 4.5m to 10.5m.
- After 18m the Bq>1 that leads a suspection of quick clay layer.
- High OCR form 0 to 4m

Plot 17. Åby data plots and interpretations

Åby (BH-10)

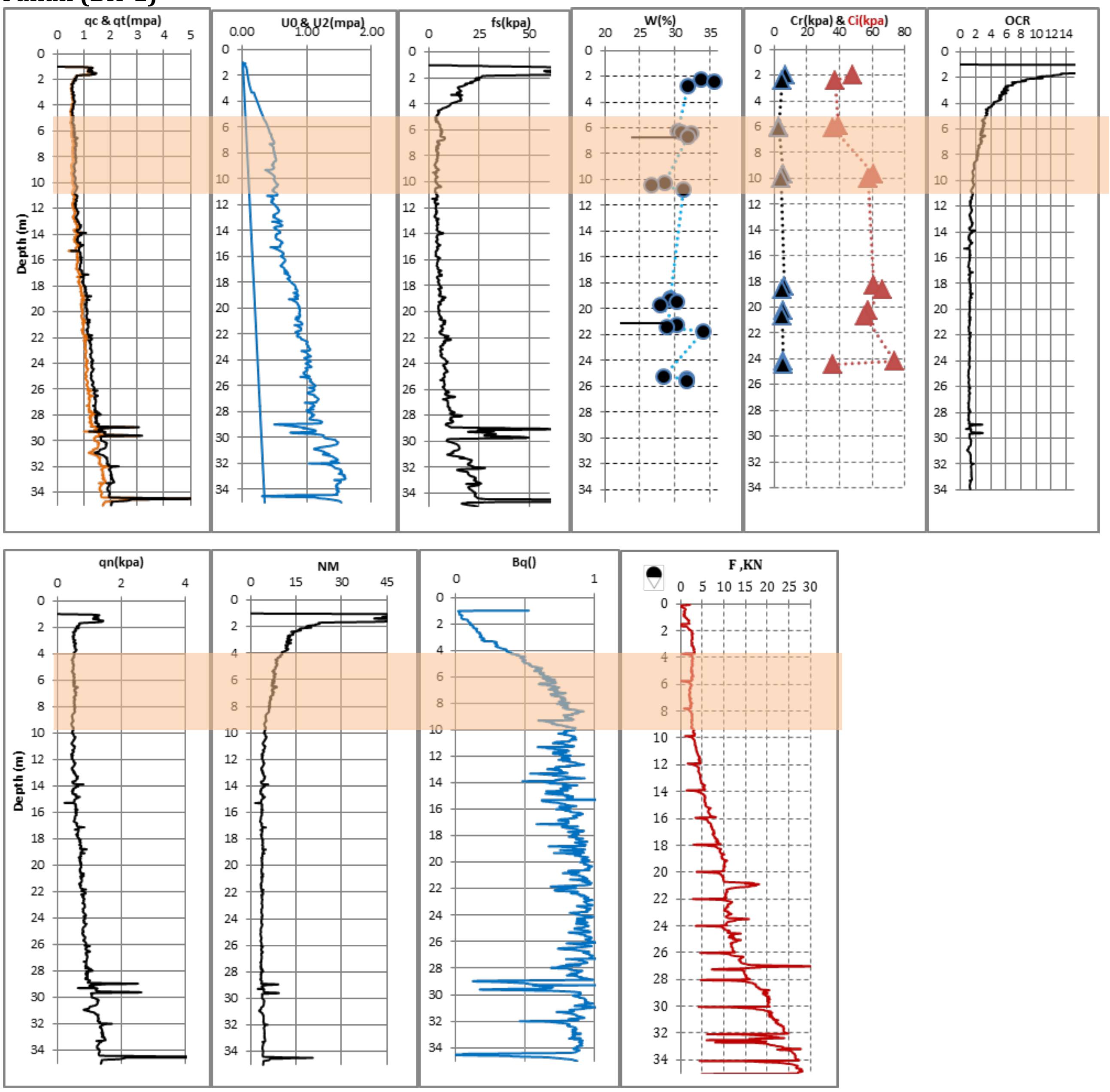


Remarks

- Linear increase in q_t and u_2 with depth
- The lab investigation shows that there is a quick clay layer from depth 4.5m to 10.5m.
- After 18m the Bq>1 that leads a suspection of quick clay layer.
- The remolded shear strength found from vane shear test is much higher than the C_{ur} from lab fall cone test.
- High OCR form 0 to 4m

Plot 18. Åby data plots and interpretations

Fallan (BH-1)

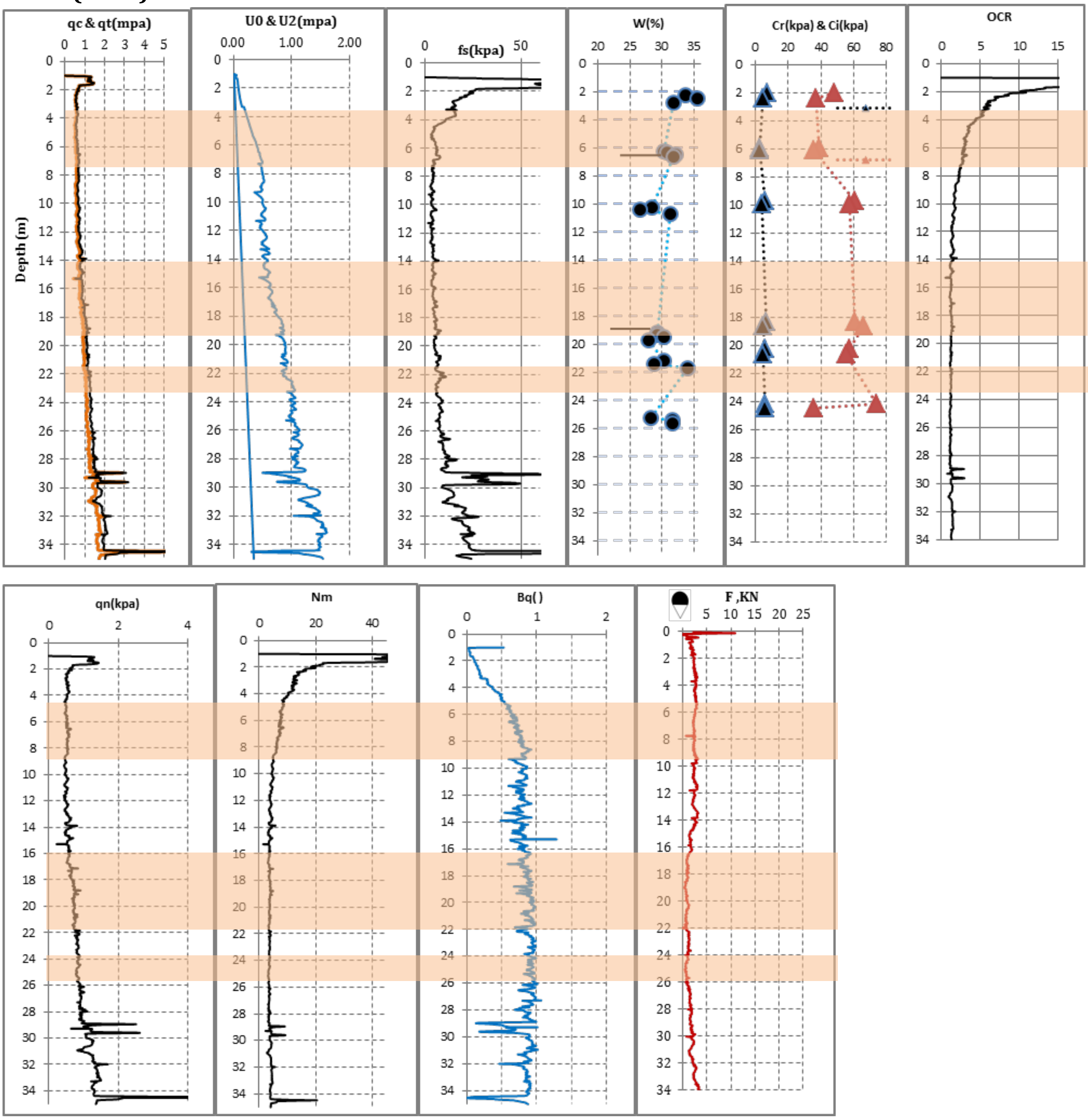


Remarks

- High u_2 relative to u_0
- The lab investigation shows no quick clay layer,but from rotary sounding plot,4m-10m the slop of the curve is vertical that shows quick clay behaviour.
- High OCR form 0 to 4m

Figure 19. Fallan data plots and interpretation

Fallan (BH-2)

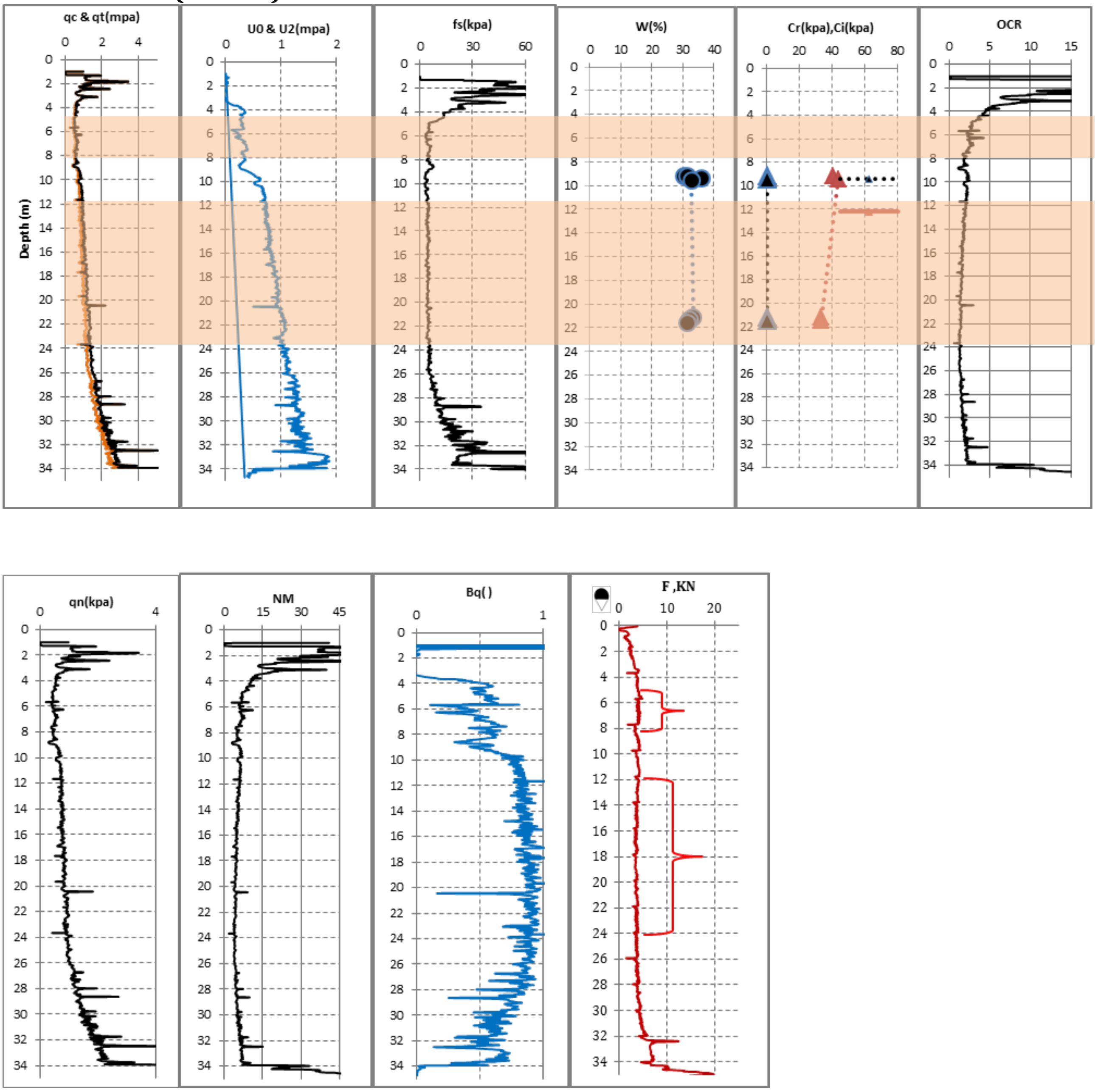


Remarks

- The lab investigation shows no quick clay layer,but from rotary sounding plot,4m-8m,15-20m and 22-24m shows the slop of the curve is vertical that shows quick clay behaviour.
- High OCR form 0 to 8m
- Lab data fromBP-1 is used due to proximity of the points where the sample taken.

Plot 20. Fallan data plots and interpretation

Kaldvelladalen (BH-109)

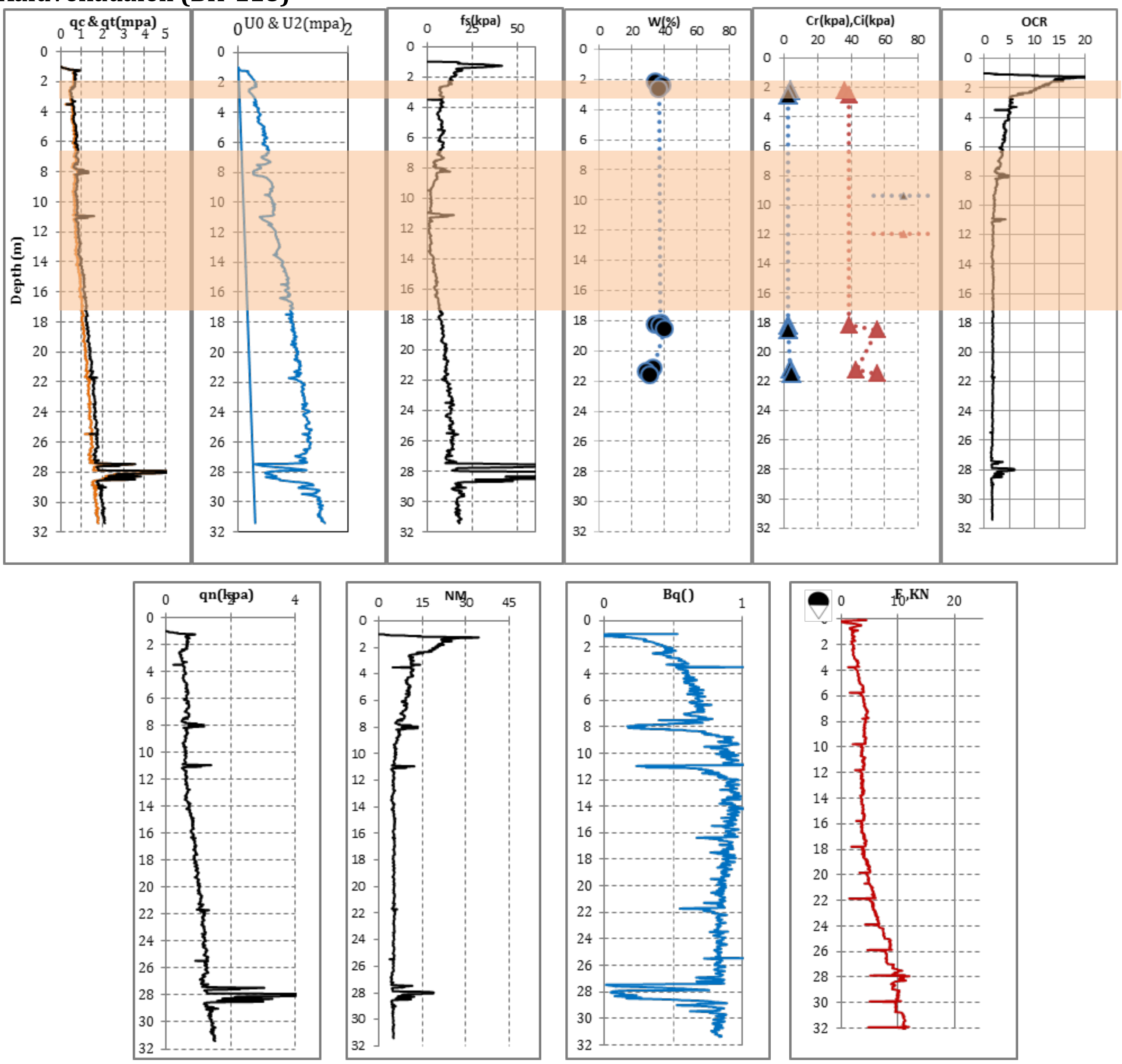


Remarks

- The lab investigation shows no quick clay layer,but from rotary sounding plot,5m-8m,12-24m shows the slop of the curve is vertical that shows quick clay behaviour.
- High OCR form 0 to 4m
- Lab fall cane test shows Cur of 0.6kpa from 9m to 24 m depth

Plot 21. Kaldvelladalen data plots and interpretation

Kaldvelladalen (BH-118)

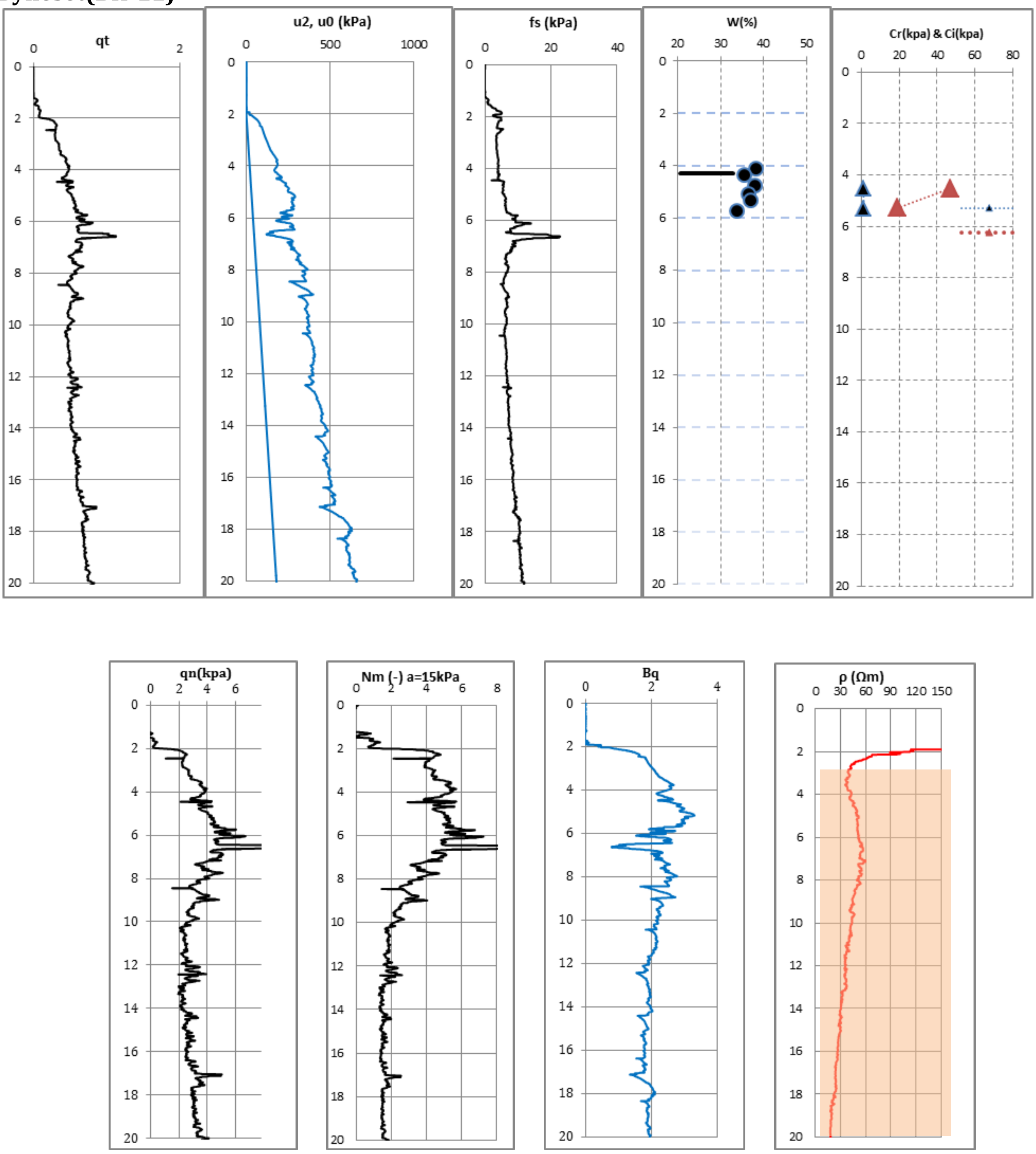


Remarks

- The lab investigation shows no quick clay layer,but from rotary sounding plot,2m-3mand from 7m-17m shows the slop of the curve is vertical that shows quick clay behaviour.
- High OCR form 0 to 4m
- Lab fall cane test shows no quick clay layer.

Plot 22. Kaldvelladalen data plots and interpretation

Byneset(BH-11)

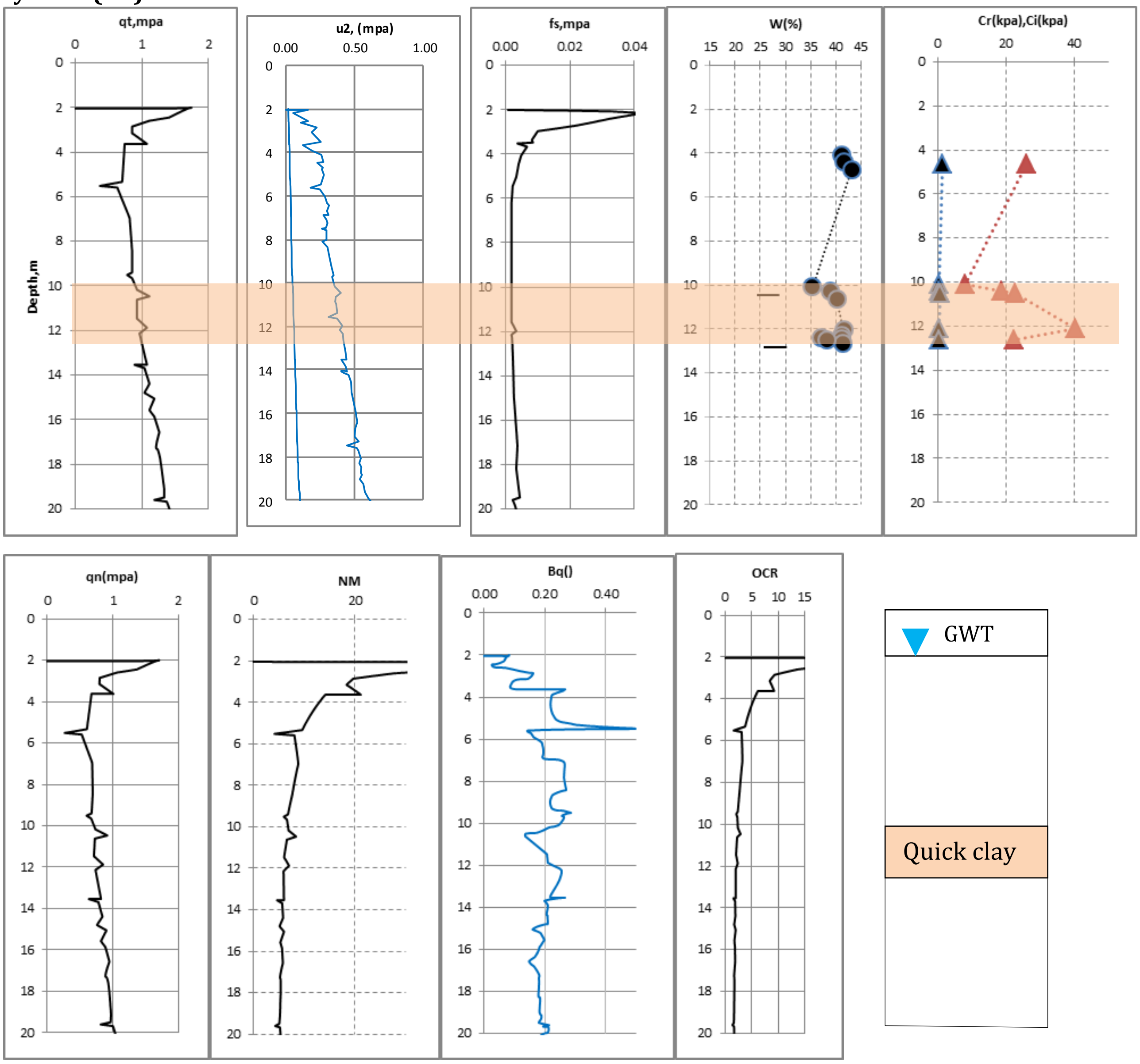


Remarks

- The lab investigation shows no quick clay layer,but high Bq value is shown on the plot
- The resistivity plot shows leached layer, which is >15Ω from 2-18m depth
- Brittle caly property is shown from 4.5m -5.3m from the lab report.(0.5kpa<Cr<2kpa)

Plot 23. Data plots and interpretation, Byneset site

Byneset(12)

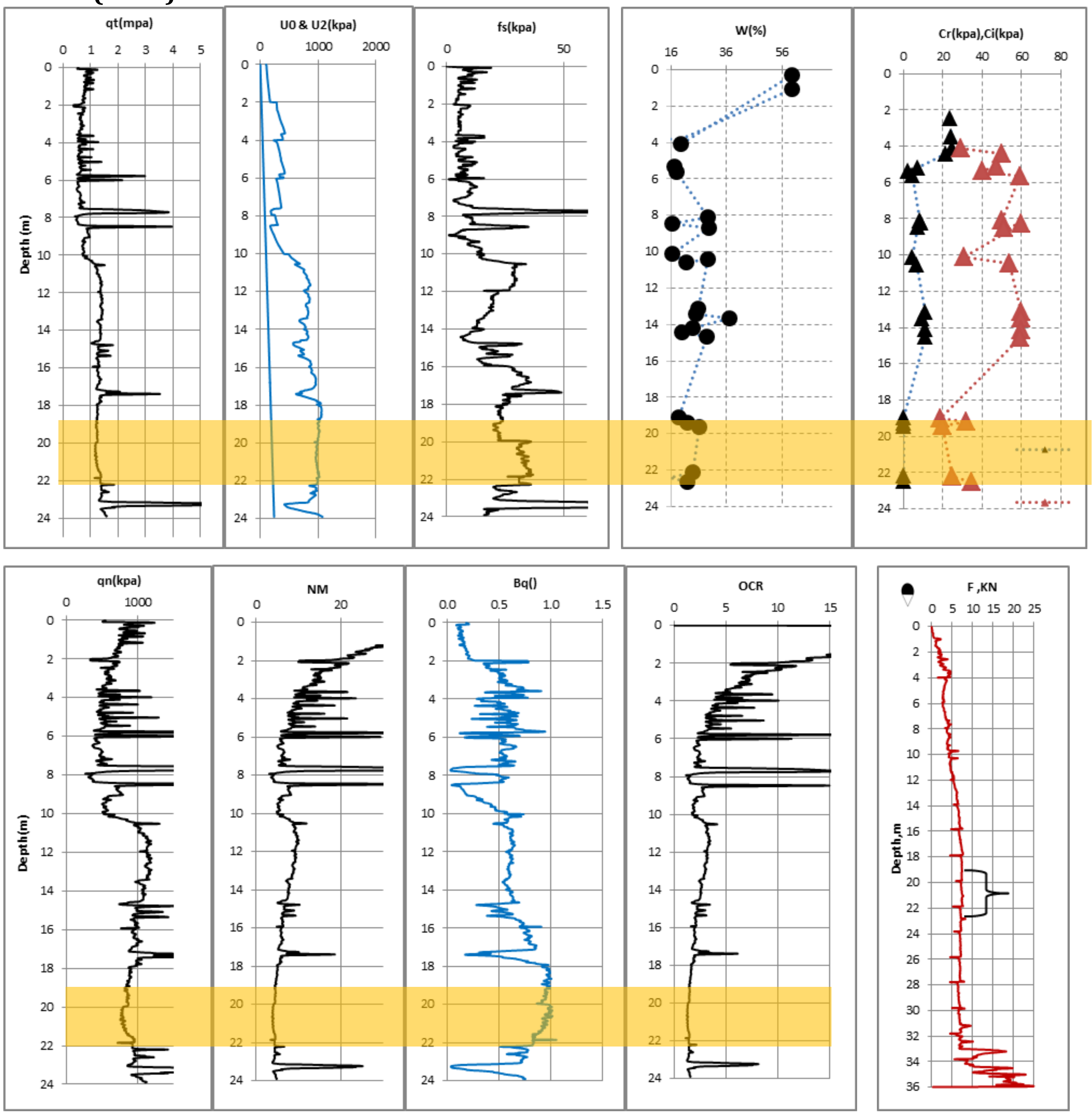


Remarks

- The lab investigation shows quick clay from 10-12.5m
- High OCR value from 2-6m shows no quick clay layer is expected within this layer.
- Quick clay layer is located even though there Bq value is very low.
- Brittle clay at 4.6m indicated from lab report.(0.5kpa<Cr<2kpa)

Plot 24. Data plots and interpretation, Byneset site

Harran (BH-9)

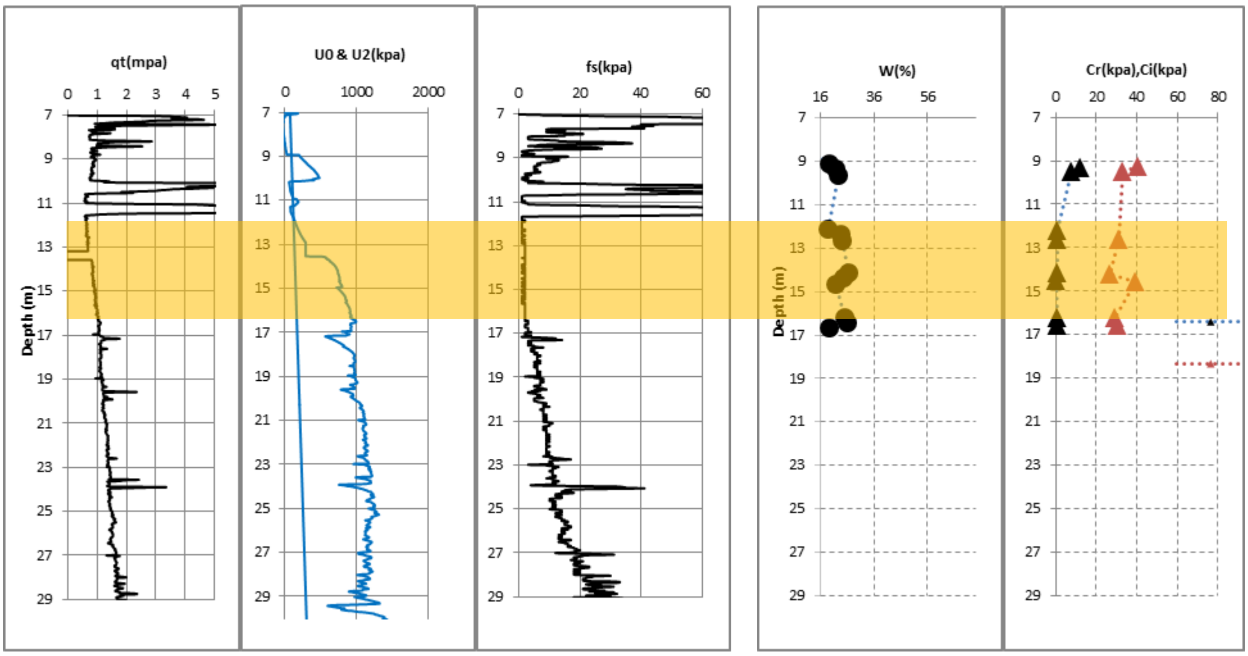


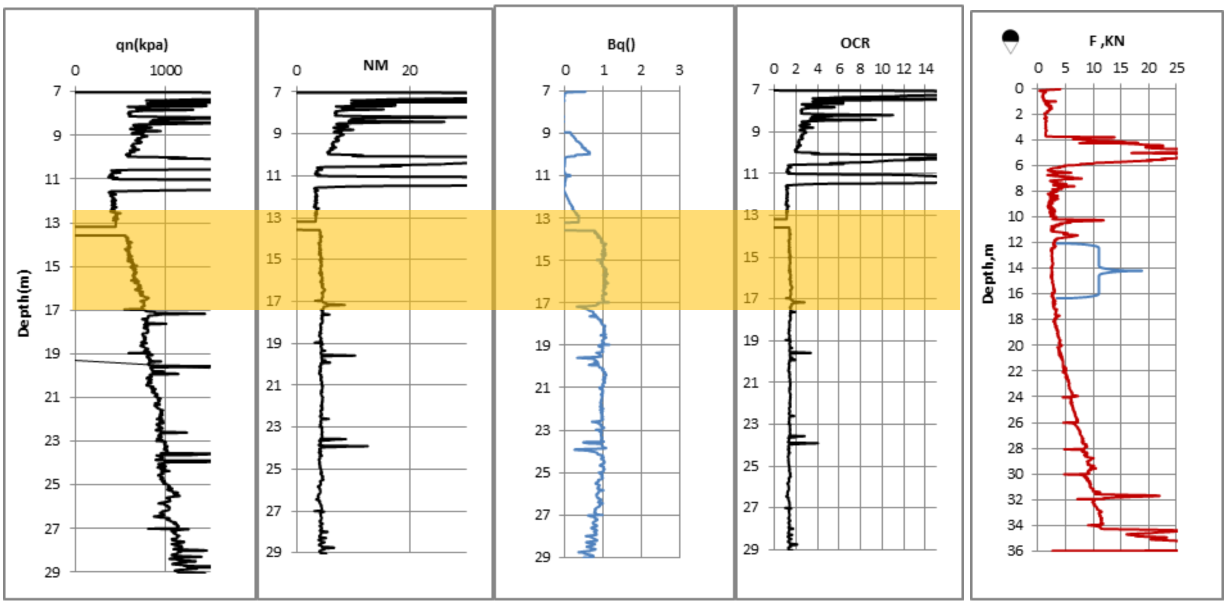
Remarks

- The lab investigation shows quick clay layer from 19m -22.5m ,Cr=0.17kpa
- High OCR value from 2-6m, and the OCR value a the location of quick clay is <2
- Bq value is <1 at the quick clay layer
- Slop of rotary sounding versus depth plot is vertical at the confirmed quick clay layer
- Location of Quick clay layer and ( ) at the rotary sounding plot

Plot 25. Data plots and interpretation

Harran (BH-15)



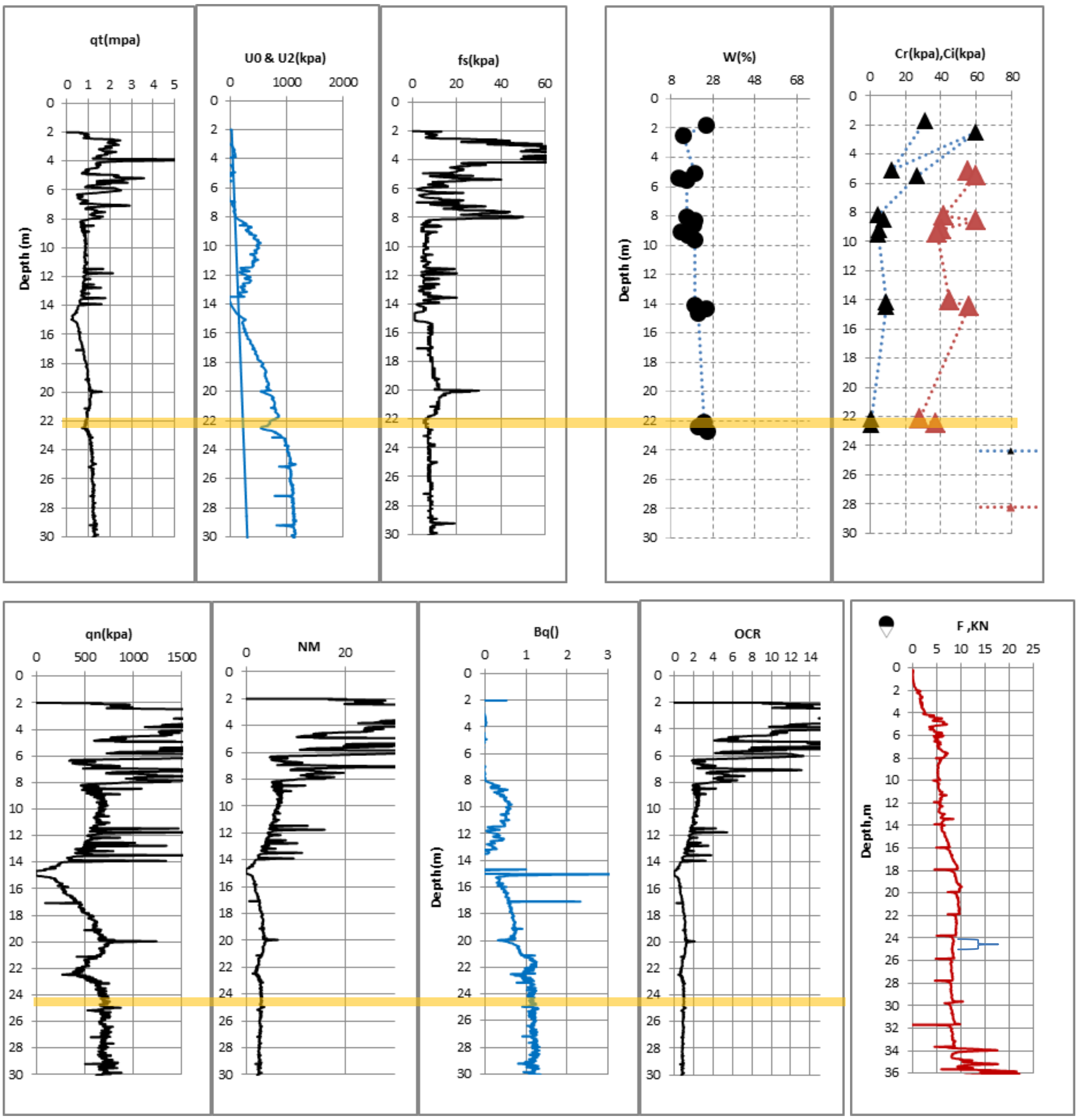


Remarks

- The lab investigation shows brittle clay layer from 12m -16.5m ,Cr=0.77kpa
- High OCR value from 7-9m, and the OCR value a the location of quick clay is <2
- Bq value is slightly >1 at the quick clay layer
- Slop of rotary sounding versus depth plot is vertical at the confirmed quick clay layer
- Location of Quick clay layer on CPTu plots and at the rotary sounding plot

Plot 26. Data plots and interpretations

Harran(BH-16)

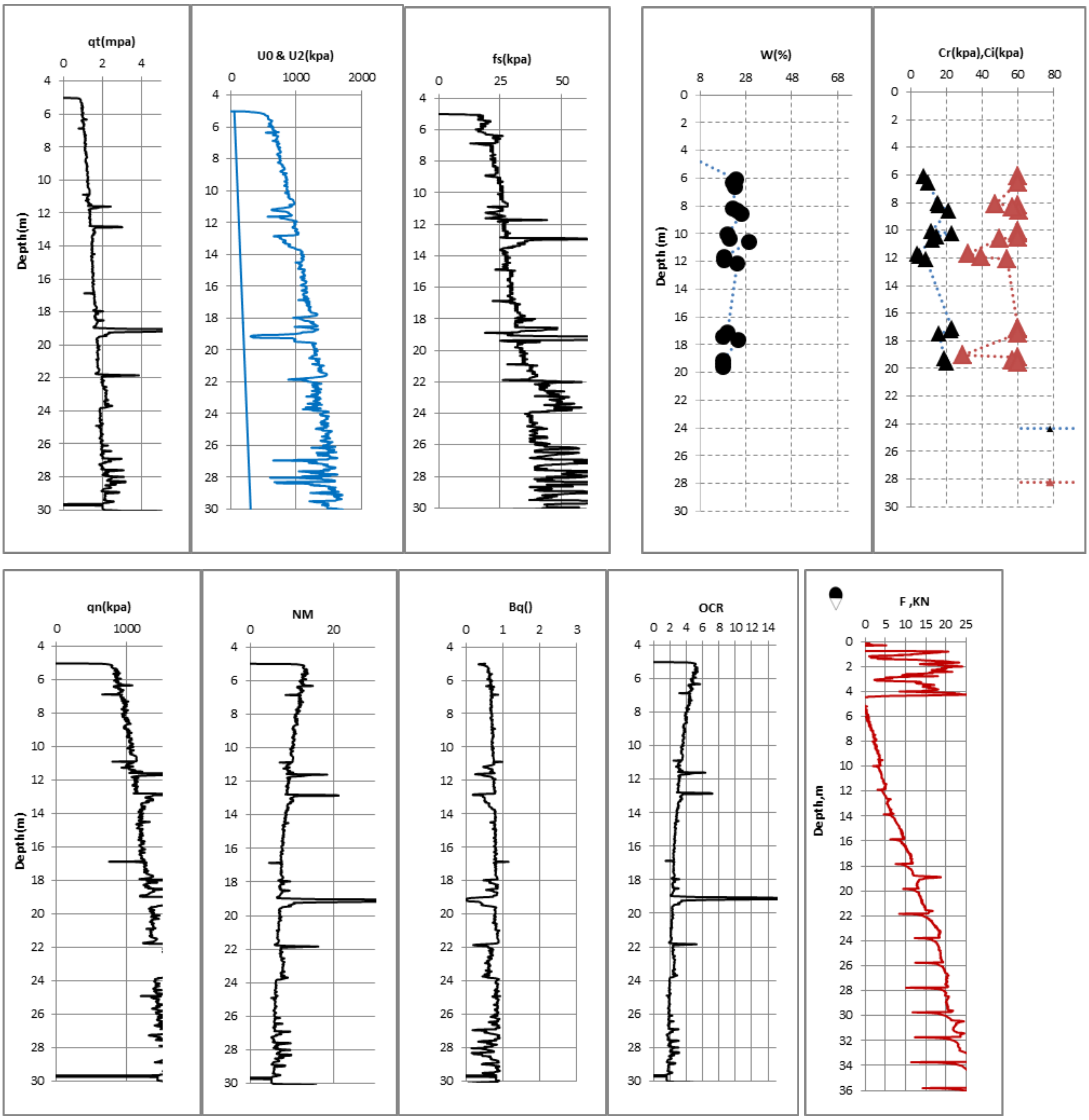


Remarks

- The lab investigation shows brittle clay layer from 22m -22.5m ,Cr=0.87kpa
- High OCR value from 2-6m, and the OCR value a the location of quick clay is <2
- Bq value is slightly >1 at the quick clay layer
- Slop of rotary sounding versus depth plot is vertical at the confirmed quick clay layer
- Thin layer of brittle or quick clay layer may be important for slop stability assessment around the area.
- Location of Quick clay layer on CPTu or sounding plots

Plot 27. Data plots and interpretations

Harran (BH-29)

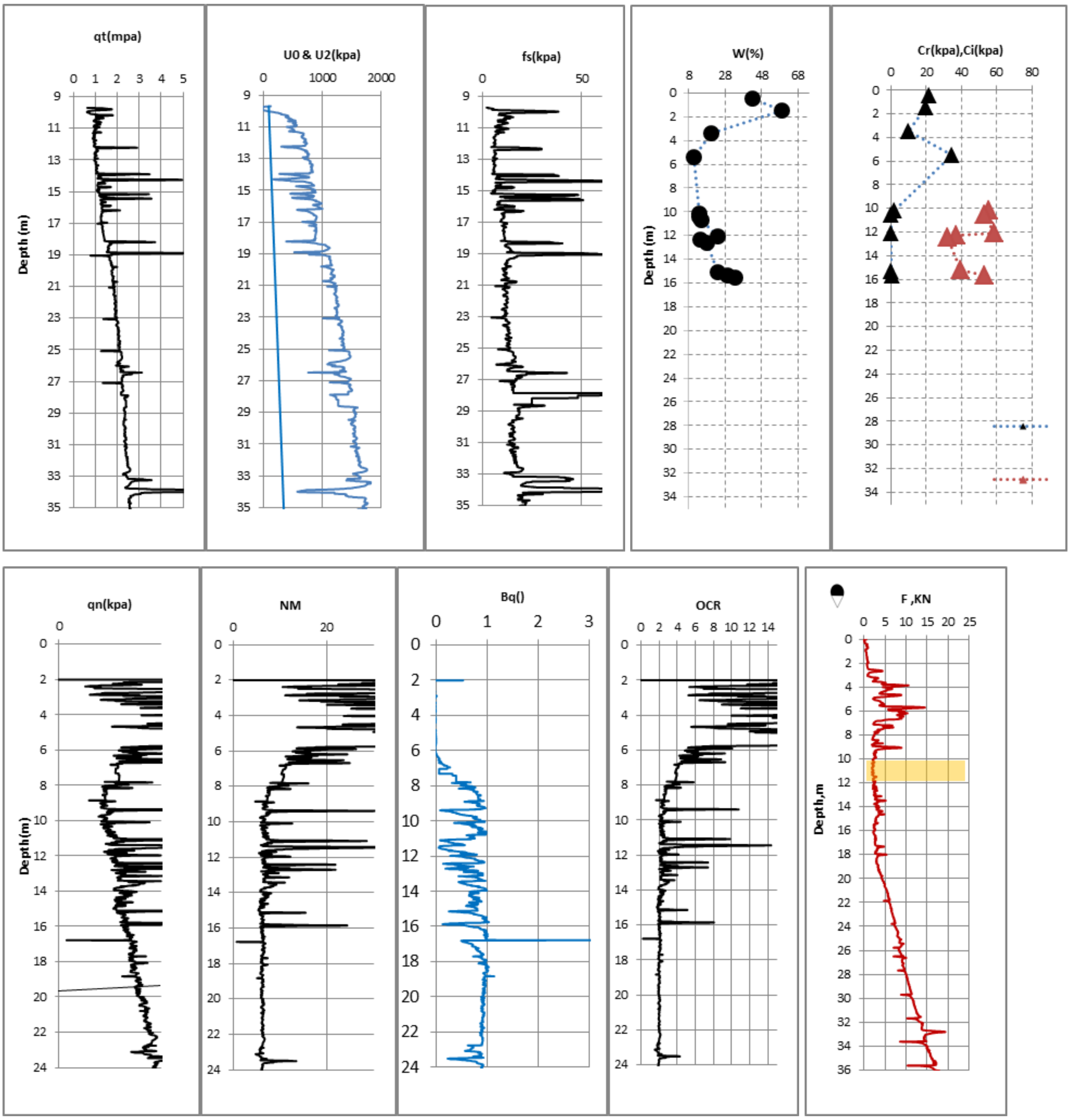


Remarks

- The lab investigation shows no quick or brittle clay layer
- OCR value of >2 through out the investigated depth
- Bq value is <1
- Slop of rotary sounding versus depth plot is increasing

Plot 28. Data plots and interpretations

Harran (BH-35)

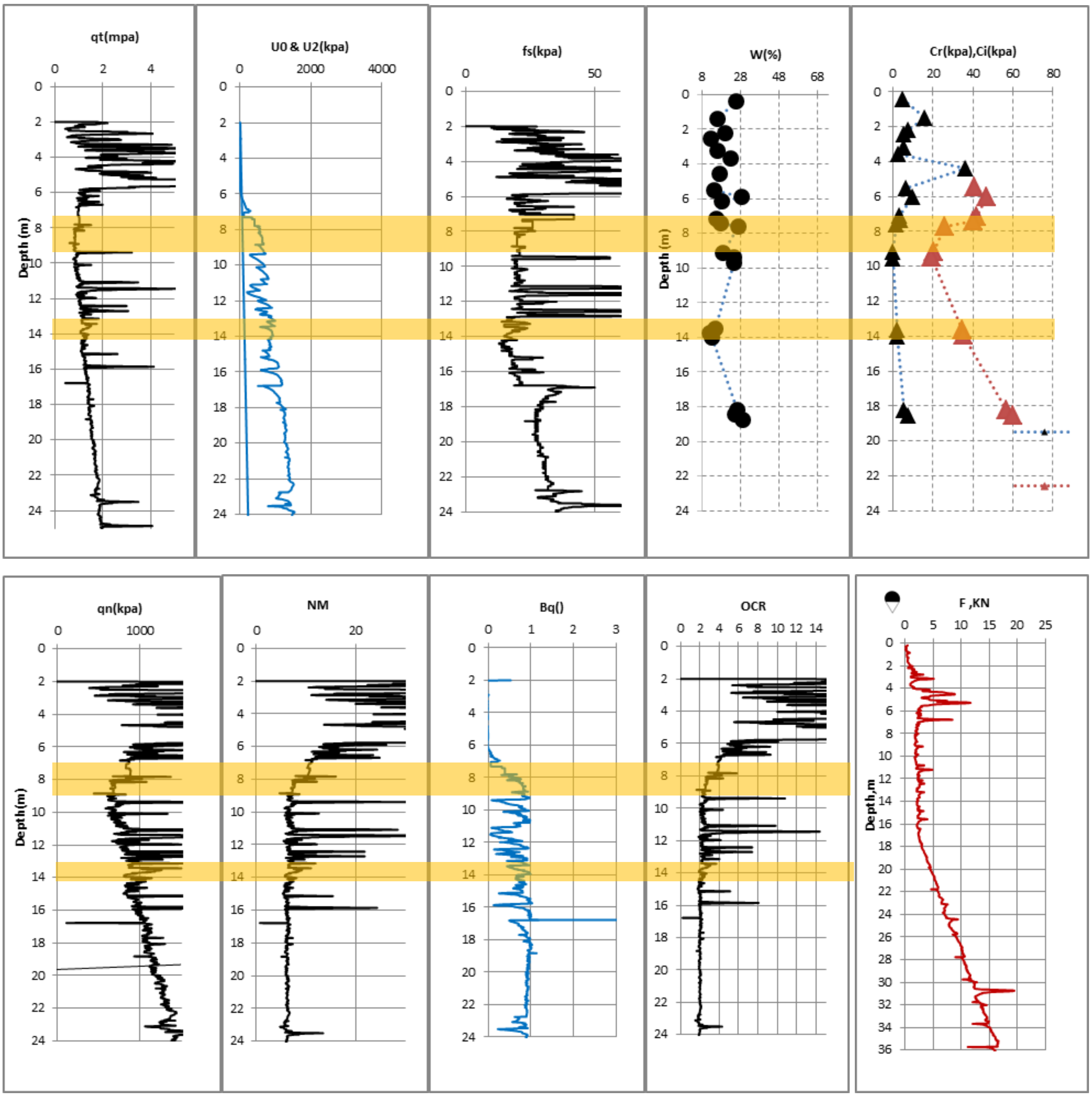


Remarks

- The lab investigation shows no quick or brittle clay layer
- OCR value of >2 through out the investigated depth and hight from 2-6m
- Bq value is <1
- Slop of rotary sounding versus depth plot shows vertical slop at depth from 10m-12m which could be the suspected quick clay layer location even though the lab investigation shows no quick or brittle clay layer

Plot 29. Data plots and interpretations

Harran (BH-38)

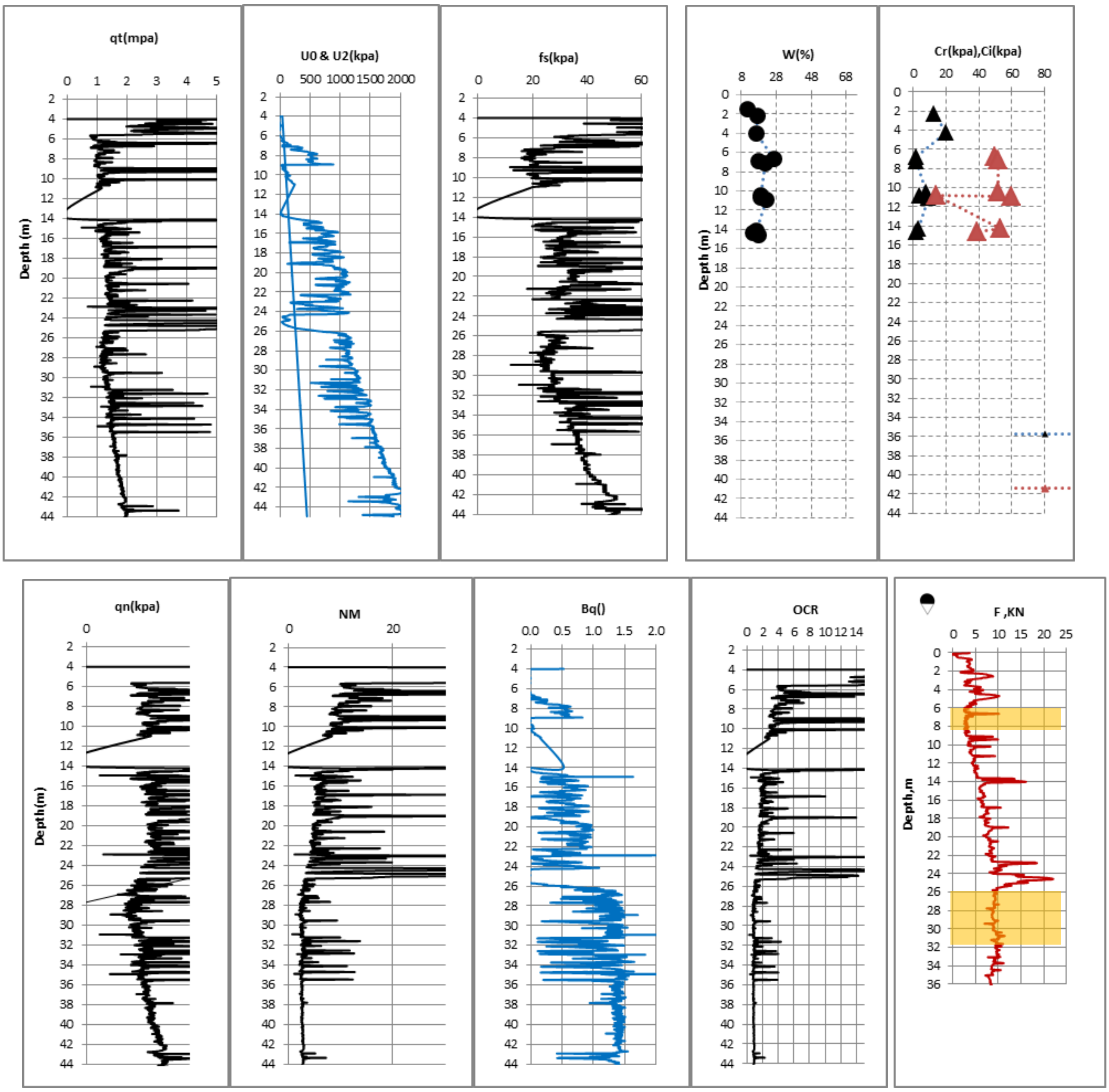


Remarks

- The lab investigation shows quick clay layer from 7.5m -9.5m i.e., $0.1 \leq Cr \leq 1.86$kpa
- Brittle clay form 13.5-14m, Cr= 2.16kpa and high OCR value from 2-6m
- Bq value is <1 at the quick clay layer location
- Slop of rotary sounding versus depth plot is vertical at the confirmed quick clay layer and the slop is increasing at the thin layer of brittle clay location
- Quick clay expected form 6m-16m depth from the slop of the sounding plot
- Location of Quick or brittle clay layer on CPTu plots

Plot 30. Data plots and interpretations

Harran (BH-45)

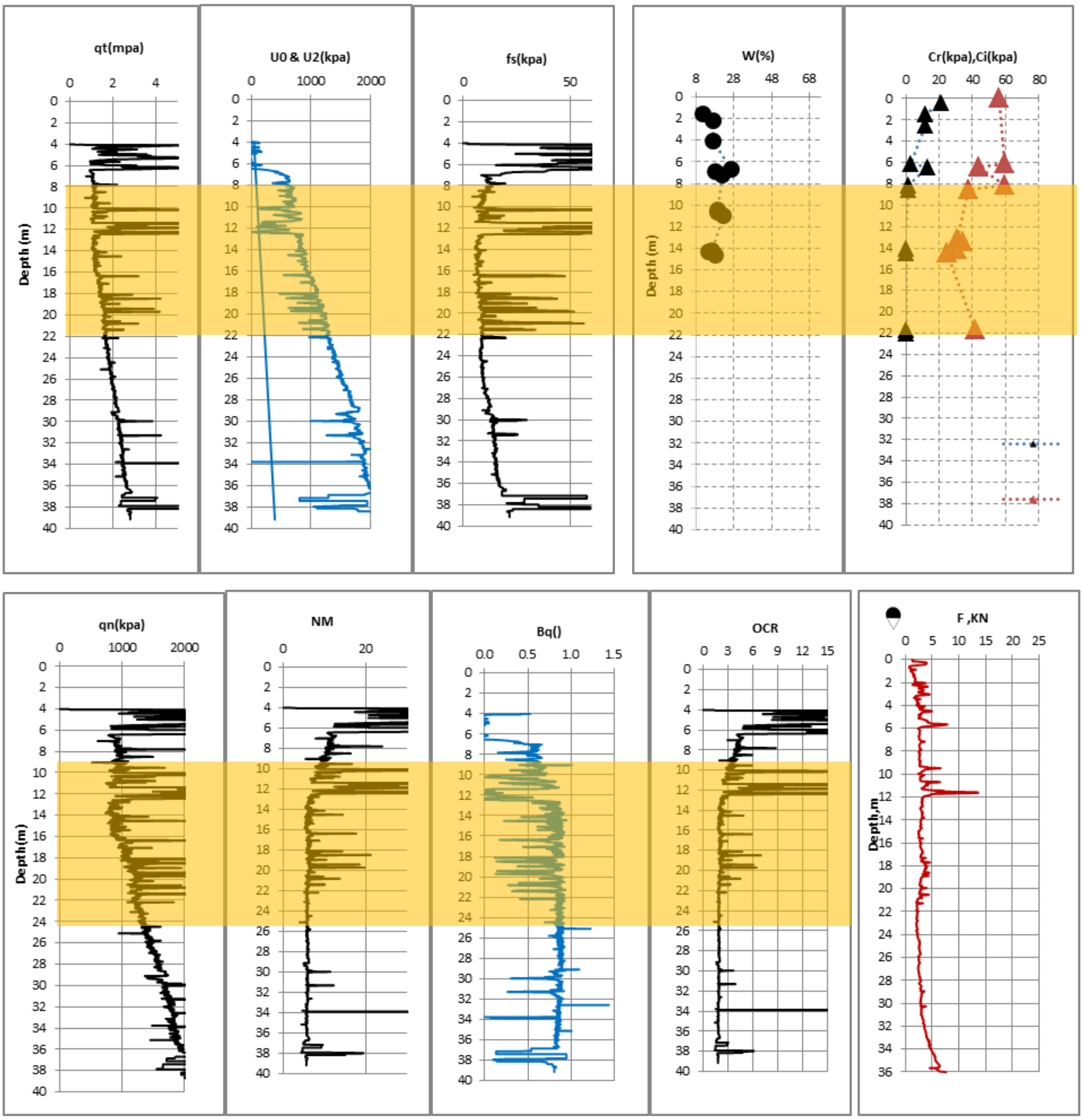


Remarks

- The lab investigation covers from 2.5m-14.5m and shows no quick or brittle clay layer.
- OCR value of >2 from 6-10m depth getting lower from depth 36m
- High Bq value from depth 26m.
- Slop of rotary sounding versus depth plot is almost vertical from 6-8.5m and from 26-32 m depth which could be the quick clay layer.
- Location of Quick or brittle clay layer on CPTu & sounding plots

Plot 31. Data plots and interpretations

Harran (BH-47)



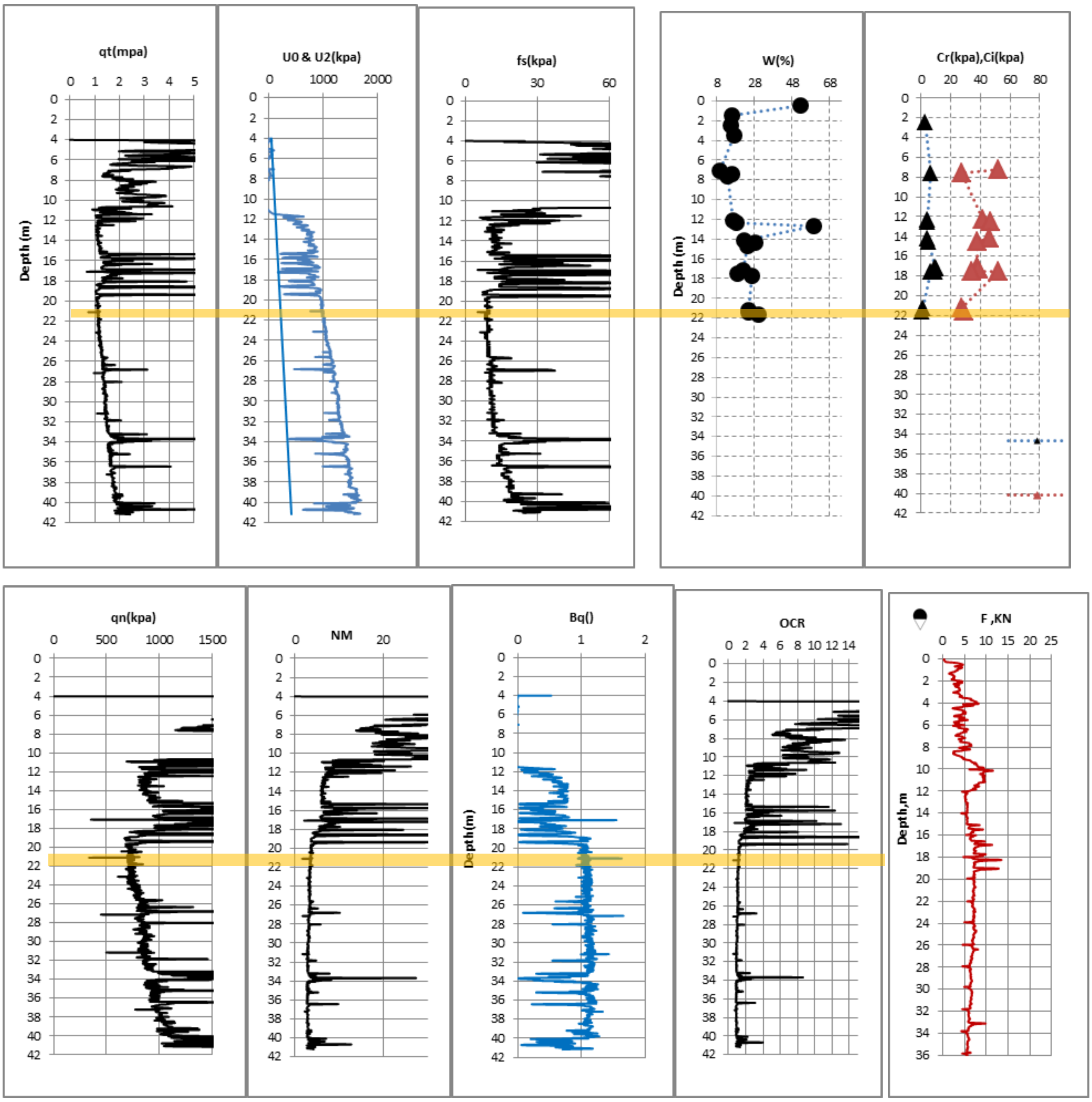
Remarks

- The laboratory investigation shows a layers of quick and brittle clay layer in between 0.15kpa $\leq$ Cr $\leq$ 1.95kpa from 8m-22m.
- Bq value is <1 at the quick clay layer location
- Slop of rotary sounding versus depth plot is vertical at the confirmed quick clay layer and quick clay expected form 22-24m depth from the slop of the sounding plot

Location of Quick or brittle clay layer on CPTu plots

Plot 32. Data plots and interpretations

Harran (BH-53)



Remarks

- The lab investigation shows brittle clay layer from 21m -22m , Cr < 2kpa
- High OCR value from4-12m, and the OCR value a the location of quick clay is <2
- Bq value is slightly >1 at the quick clay layer
- Slop of rotary sounding versus depth plot is vertical with some pick resistances and vertical slop from 12-14.5m and from 22m downwards
- Location of Quick clay layer on CPTu or sounding plots

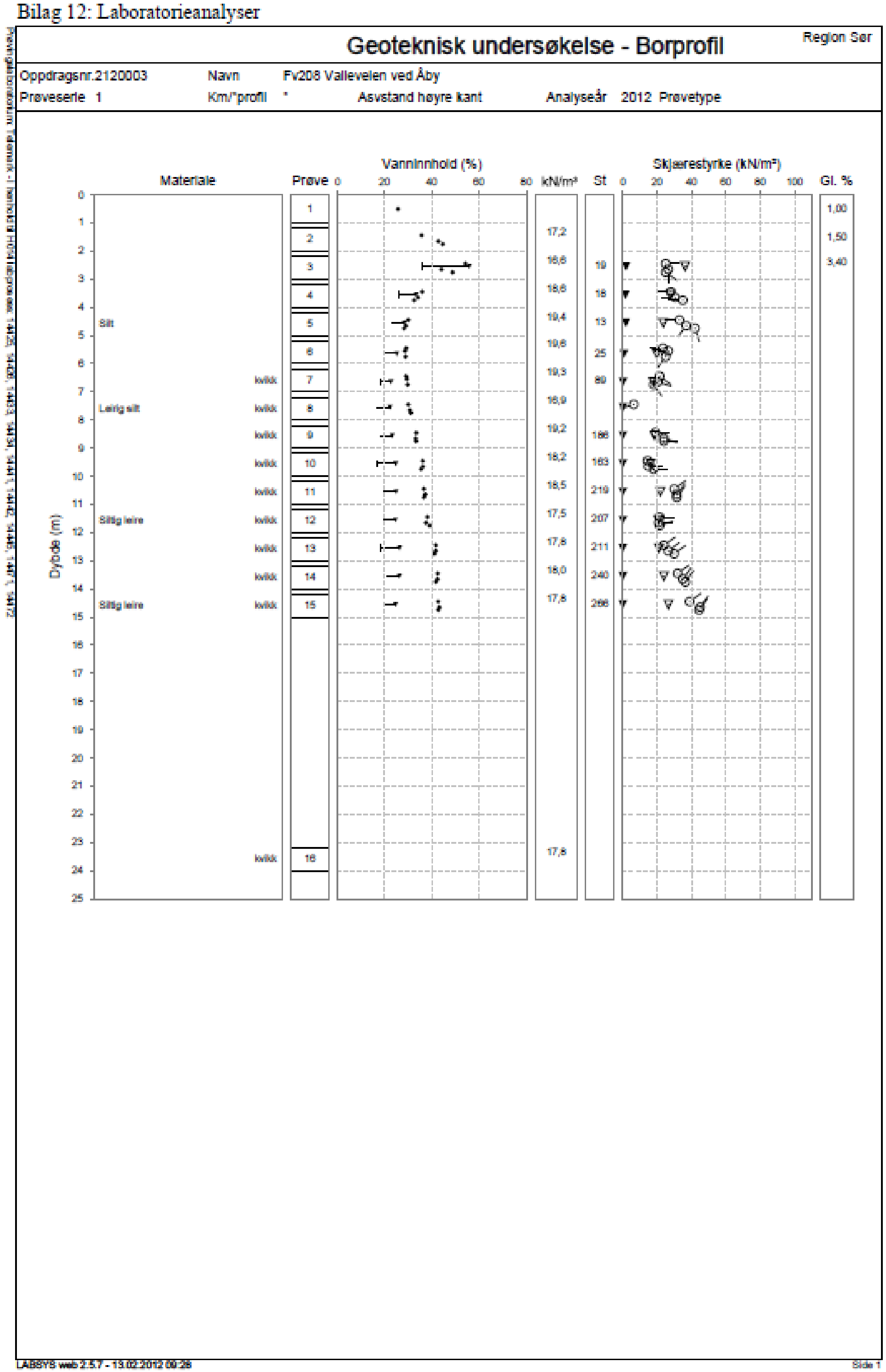
Plot 33. Data plots and interpretations

Appendix 2 –
Laboratory data profile with extracted data calculations

Åby site

Bore hole no. 1

Bilag 12: Laboratorieanalyser

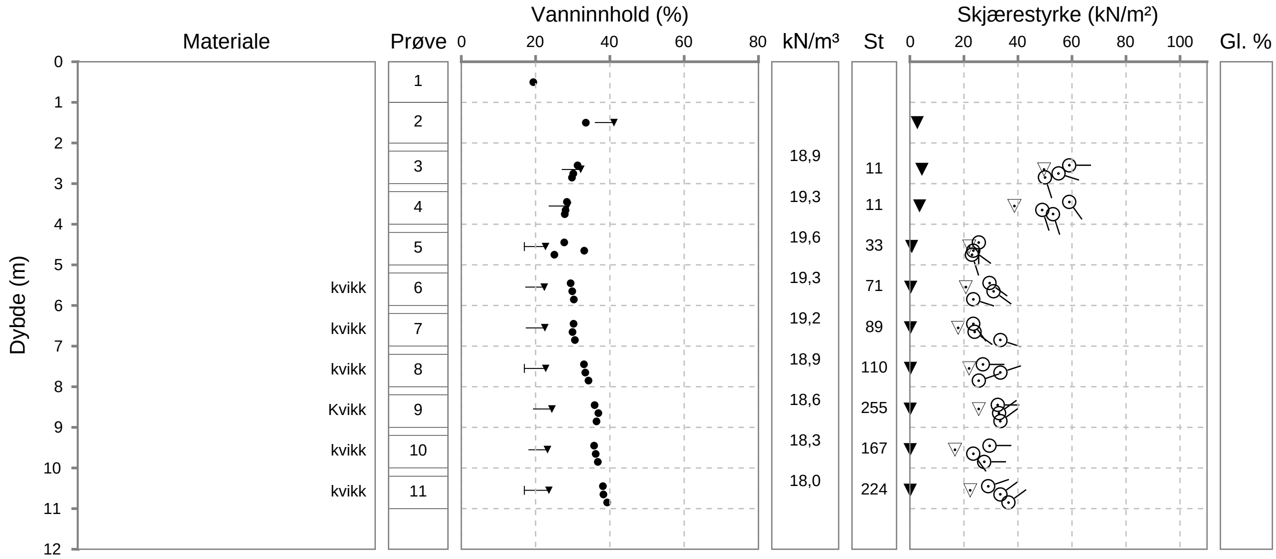


Geoteknisk undersøkelse - Borprofil

Region Sør

Oppdragsnr.2120003 Navn Fv208 Valleveien ved Åby

Prøveserie 150 Km/*profil * Asvstand høyre kant Analyseår 2012 Prøvetype



Geoteknisk undersøkelse - Borprofil
Merknader

Oppdrag - 2120003

Prøveserie: 5

Dato	Merknad
2012-02-01	Prøvene er tatt opp i Hull 10A med stålsylindere og analysert i Labcontainer på stedet av Gro Elin Vrangsund og Anniken Setalid.
2012-01-31	Dybde fra 0,0m til 8,0m er tatt opp og analysert den 30.01.12. Dybde 8,2-9,0 stod i bakken over natten fra den 30.01.12 til 31.01. 12 og ble analysert den 31.01.12. Dybde fra 9,2 til 11,0 m ble tatt opp og analysert den 31.01.12.

Åby laboratory data calculated

Bore hole no. 1

w(%)		Remolded		Intact			Uniaxial	
w	Depth	Cr	Depth	Ci	Depth	St=Ci/Cr	F	Depth
34.21	0.48	1.32	2.49	36.27	2.49	27.39	24.62	2.45
47.30	1.40	0.66	3.49	27.53	3.49	41.57	26.07	2.67
57.36	1.62	1.32	4.49	23.16	4.49	17.49	24.62	2.71
59.37	1.74	0.10	5.62	19.52	5.62	195.18	27.53	3.42
72.45	2.44	0.10	6.58	18.06	6.58	180.61	29.72	3.64
59.37	2.60	0.66	7.50	18.06	7.50	27.27	34.09	3.73
64.91	2.72	0.10	8.51	15.15	8.51	151.47	31.90	4.48
47.80	3.45	0.66	9.51	21.70	9.51	32.77	37.00	4.66
45.79	3.60	0.10	10.51	20.25	10.51	202.47	42.10	4.75
42.77	3.73	0.66	12.52	20.98	12.52	31.67	22.43	5.41
40.25	4.42	0.15	11.50	23.16	11.50	153.57	26.07	5.54
38.24	4.64	0.15	13.49	26.07	13.49	172.89	23.89	5.72
37.23	4.80	0.15	14.50		14.50		20.98	6.42
39.75	5.40						20.25	6.69
38.74	5.50						17.33	6.78
38.24	5.75						5.68	7.44
38.24	6.41						18.06	8.45
39.75	6.50						23.16	8.67
39.75	6.72						23.16	8.72
40.25	7.45						13.69	9.42
41.26	7.58						14.42	9.60
41.26	7.73						18.06	9.73
44.28	8.43						29.72	10.44
43.27	8.62						30.45	10.62
45.28	8.74						31.90	10.75
47.80	9.43						20.98	11.45
48.30	9.62						20.25	11.68
46.79	9.75						20.98	11.72
48.81	10.47						23.16	12.43
50.31	10.63						25.35	12.65
48.81	10.73						29.72	12.78
50.82	11.42						31.17	13.49
49.81	11.61						34.82	13.66
51.82	11.70						36.27	13.75
56.35	12.46						38.46	14.46
55.85	12.59						44.29	14.63
54.84	12.71						44.29	14.72
56.35	13.44							
56.86	13.63							
55.85	13.75							
56.86	14.45							
57.86	14.63							
56.86	14.76							

Åby laboratory data calculated

Bore hole no. 9 and 10

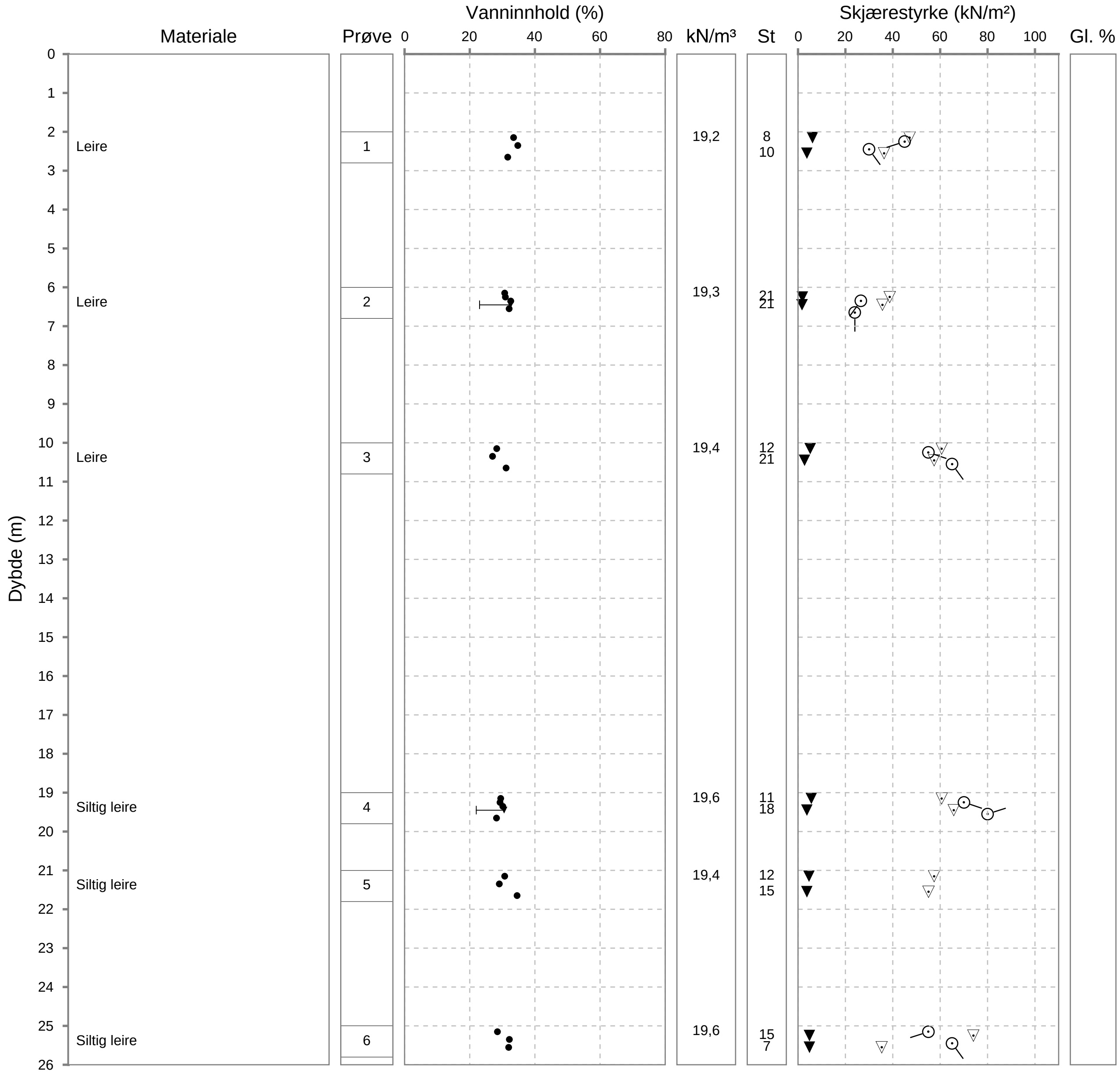
w(%)		Remolded		Intact			Uniaxial	
w	Depth	Cr	Depth	Ci	Depth	St=Ci/Cr	F	Depth
19	0.48	2.39	1.45	49.40	1.45	21	58.96	2.54
34	1.51	4.38	2.59	38.65	2.59	9	54.98	2.72
31	2.54	3.59	3.49	21.51	3.49	6	49.80	2.86
30	2.74	0.40	4.47	21.12	4.47	53	58.96	3.44
30	2.82	0.40	5.47	17.53	5.47	44	52.59	3.75
28	3.42	0.40	6.48	21.91	6.48	55	49.00	3.62
28	3.62	0.40	7.48	25.50	7.48	64	25.10	4.44
28	3.74	0.40	8.49	16.33	8.49	41	23.11	4.63
27	4.45	0.40	9.46	21.91	9.46	55	23.11	4.73
25	4.74	0.40	10.47		10.47		29.48	5.45
33	4.65						30.68	5.63
29	5.45						23.11	5.84
30	5.65						23.11	6.45
30	5.83						23.51	6.64
30	6.45						33.47	6.82
30	6.65						27.09	7.43
30	6.85						25.10	7.83
33	7.43						33.47	7.61
33	7.63						31.87	8.41
34	7.83						33.07	8.65
35	8.43						33.07	8.83
37	8.63						29.48	9.41
36	8.83						23.51	9.62
36	9.43						27.49	9.81
36	9.63						28.69	10.42
37	9.83						33.47	10.60
38	10.43						36.25	10.81
38	10.63							

Geoteknisk undersøkelse - Borprofil

Region Midt

Oppdragsnr.4110041 Navn E6 Hagga Skjeringstad

Prøveserie 1 Km/*profil *1 Asvstand høyre kant Analyseår 2011 Prøvetype 54 mm



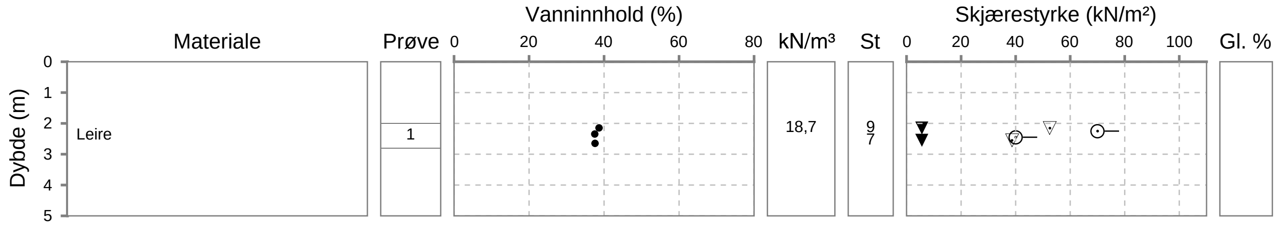
Prøvingslaboratorium: Sentrallaboratoriet Trondheim - I henhold til H014 labprosess: 14425, 14426, 14433, 14434, 14441, 14442, 14471, 14472

Geoteknisk undersøkelse - Borprofil

Region Midt

Oppdragsnr.4110041 Navn E6 Hagga Skjeringstad

Prøveserie 2 Km/*profil *2 Asvstand høyre kant Analyseår 2011 Prøvetype 54 mm



Prøvingslaboratorium: Sentrallaboratoriet Trondheim - I henhold til H014 labprosess: 14425, 14426, 14471, 14472

Geoteknisk undersøkelse - Borprofil
Merknader

Oppdrag - 4110041

Prøveserie: 1

Dato	Merknad
2011-04-20	(Geoprovenr. 6): Grå myk leiremasse med tynne siltelag i B og A-bitene.
2011-04-20	(Geoprovenr. 5): Grå myk leiremasse med tynne siltelag i E og F-endene.
2011-04-20	(Geoprovenr. 4): Grå fast leiremasse.Ren og jevn.
2011-04-20	(Geoprovenr. 3): Grå myk leiremasse.Jevn og ren.
2011-04-20	(Geoprovenr. 2): Grå myk leiremasse.Ren,jevn og fin.
2011-04-20	(Geoprovenr. 1): Brun myk leiremasse.Mye oksidert.

Prøveserie: 2

Dato	Merknad
2011-04-20	(Geoprovenr. 1): Brun-grå leiremasse.Veldig oksidert.

Fallan site

Bore hole 1, Laboratory data calculated

w(%)		Remolded		Intact			Uniaxial	
w	Depth	Cr	Depth	Ci	Depth	St=Ci/Cr	F	Depth
33.68466	2.256263	7.051282	2.001511	48.07692	2.001511	6.82	45.51282	2.190332
35.55537	2.45246	4.487179	2.379154	37.17949	2.416919	8.29	30.76923	2.34139
31.80758	2.766375	2.564103	5.966767	39.10257	5.929003	15.25	27.5641	6.117825
30.37214	6.219439	2.564103	6.117825	35.89743	6.117825	14.00	24.35897	6.382175
30.83921	6.337157	5.769231	9.705438	60.89743	9.705438	10.56	55.1282	9.856496
32.24251	6.454875	3.846154	9.969789	57.69231	9.969789	15.00	65.38461	10.15861
31.77262	6.651072	6.410256	18.35347	60.89743	18.31571	9.50	69.8718	18.50453
28.46365	10.22185	4.487179	18.61782	66.02564	18.65559	14.71	80.1282	18.80665
26.58939	10.41805	5.769231	20.27946	57.69231	20.27946	10.00	55.76923	24.16918
31.26777	10.73197	4.487179	20.6571	55.76923	20.6571	12.43	65.38461	24.43353
29.31902	19.20767	5.769231	24.20695	73.71795	24.16918			
29.31796	19.32539	5.769231	24.4713	35.89743	24.4713			
30.25278	19.48234							
27.91006	19.71778							
30.23724	21.20888							
28.83111	21.40507							
33.97762	21.71899							
28.32874	25.21129							
31.60382	25.40749							
31.60205	25.60368							

Bore hole 1,

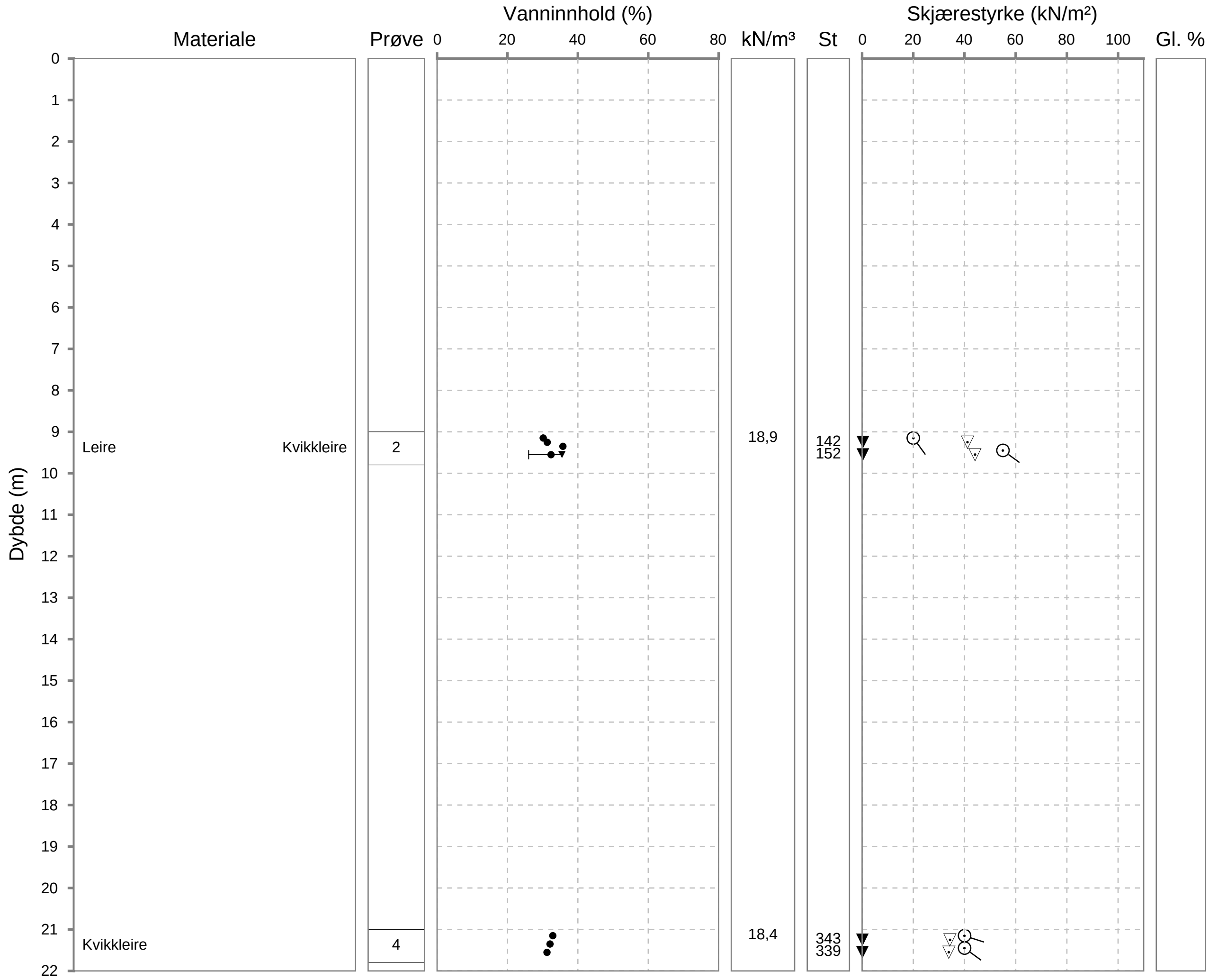
w(%)		Remolded		Intact			Uniaxial	
w	Depth	Cr	Depth	Ci	Depth	St=Ci/Cr	F	Depth
38.51852	2.117117	4.512821	2.019749	41.84615	2.019749	9.27	55.79487	2.244165
37.40741	2.342342	4.512821	2.423698	30.76923	2.468582	6.82	32	2.423698
37.40741	2.612613							

Geoteknisk undersøkelse - Borprofil

Region Midt

Oppdragsnr.4110041 Navn E6 Hagga Skjeringstad

Prøveserie 7 Km/*profil *109 Asvstand høyre kant Analyseår 2011 Prøvetype 54 mm



Geoteknisk undersøkelse - Borprofil
Merknader

Oppdrag - 4110041

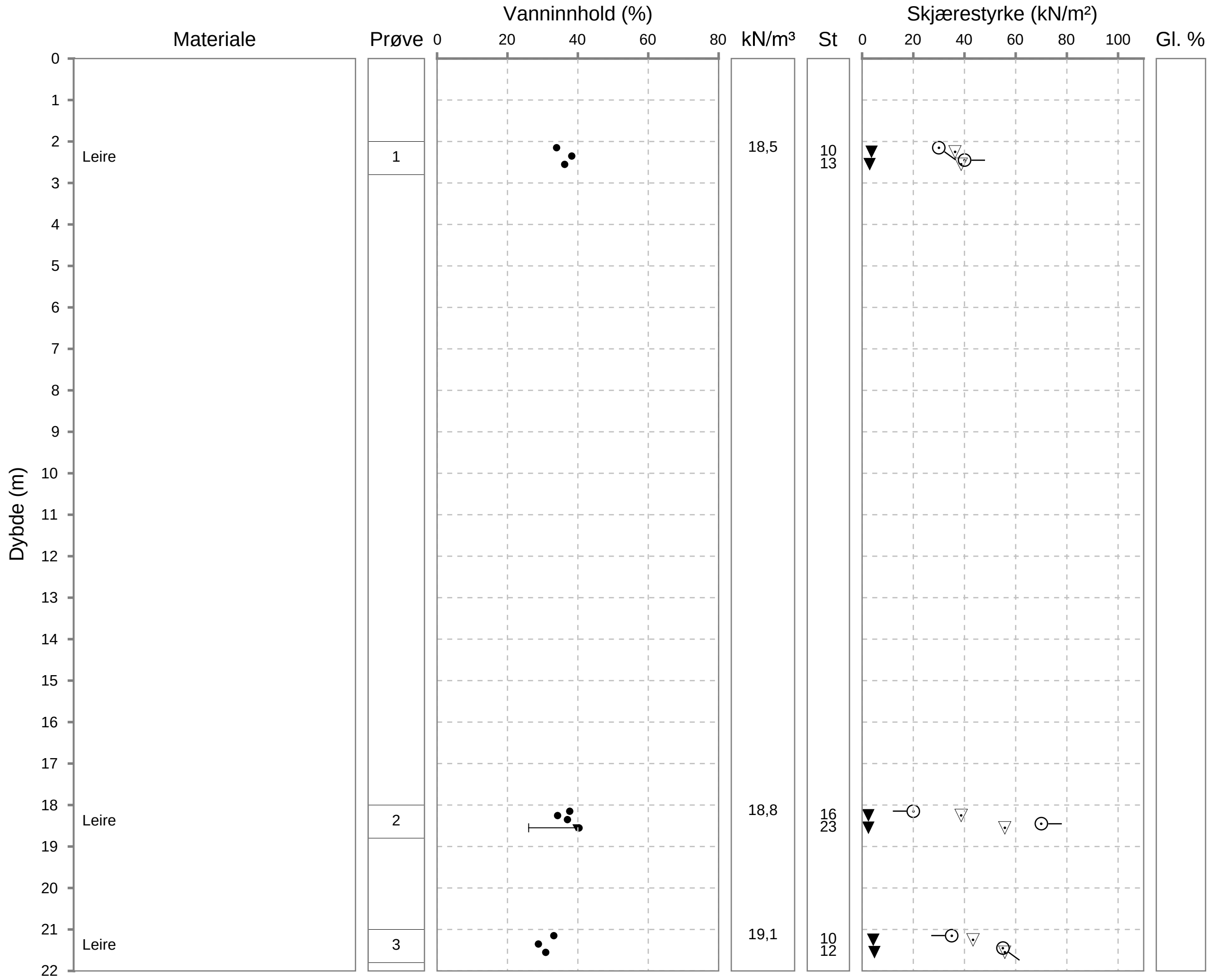
Prøveserie: 7

Dato	Merknad
2011-05-20	(Geoprovenr. 4): Grå sensitiv leiremasse.Kvikkleire.
2011-05-20	(Geoprovenr. 2): Grå sensitiv leiremasse.Kvikkleire.

Geoteknisk undersøkelse - Borprofil

Region Midt

Oppdragsnr.4110041	Navn	E6 Hagga Skjeringstad			
Prøveserie 6	Km/*profil	*118	Asvstand høyre kant	Analyseår 2011	Prøvetype 54 mm



Geoteknisk undersøkelse - Borprofil
Merknader

Oppdrag - 4110041

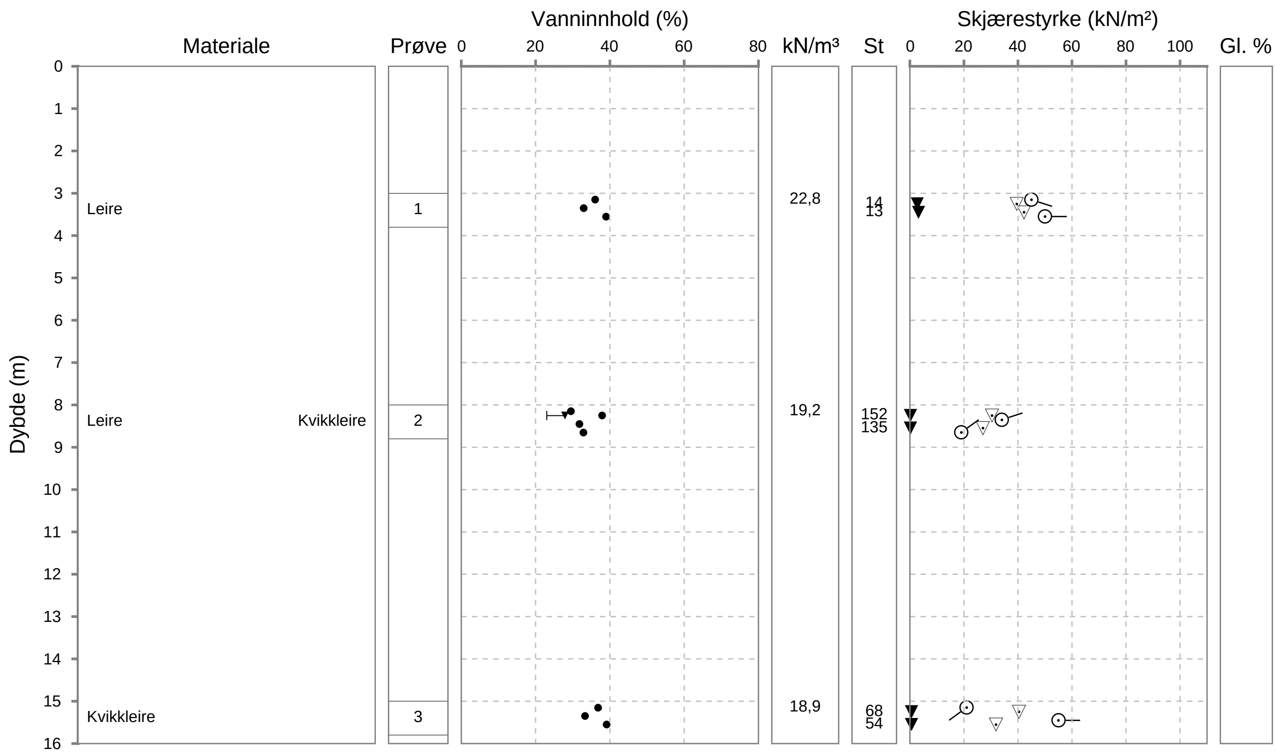
Prøveserie: 6

Dato	Merknad
2011-05-13	(Geoprovenr. 3): Grå,myk leiremasse.Noe tynne siltelag mot E-enden.Et siltelag i A-biten.
2011-05-13	(Geoprovenr. 2): Grå myk,ren og jevn leiremasse.
2011-05-13	(Geoprovenr. 1): Grå myk leiremasse.Mye oksidert.

Geoteknisk undersøkelse - Borprofil

Region Midt

Oppdragsnr.4110041	Navn	E6 Hagga Skjeringstad					
Prøveserie 3	Km/*profil	*106	Asvstand høyre kant	Analyseår	2011	Prøvetype	54 mm



Geoteknisk undersøkelse - Borprofil
Merknader

Oppdrag - 4110041

Prøveserie: 3

Dato	Merknad
2011-05-13	(Geoprovenr. 3): Grå,myk,sensitiv leiremasse.Kvikkleire.
2011-05-13	(Geoprovenr. 2): Grå,myk,sensitiv leiremasse. Kvikkleire.
2011-05-13	(Geoprovenr. 1): Grå, myk,jevn og ren leiremasse.

Kaldveladalen

Bore hole no.109, Laboratory data calculated

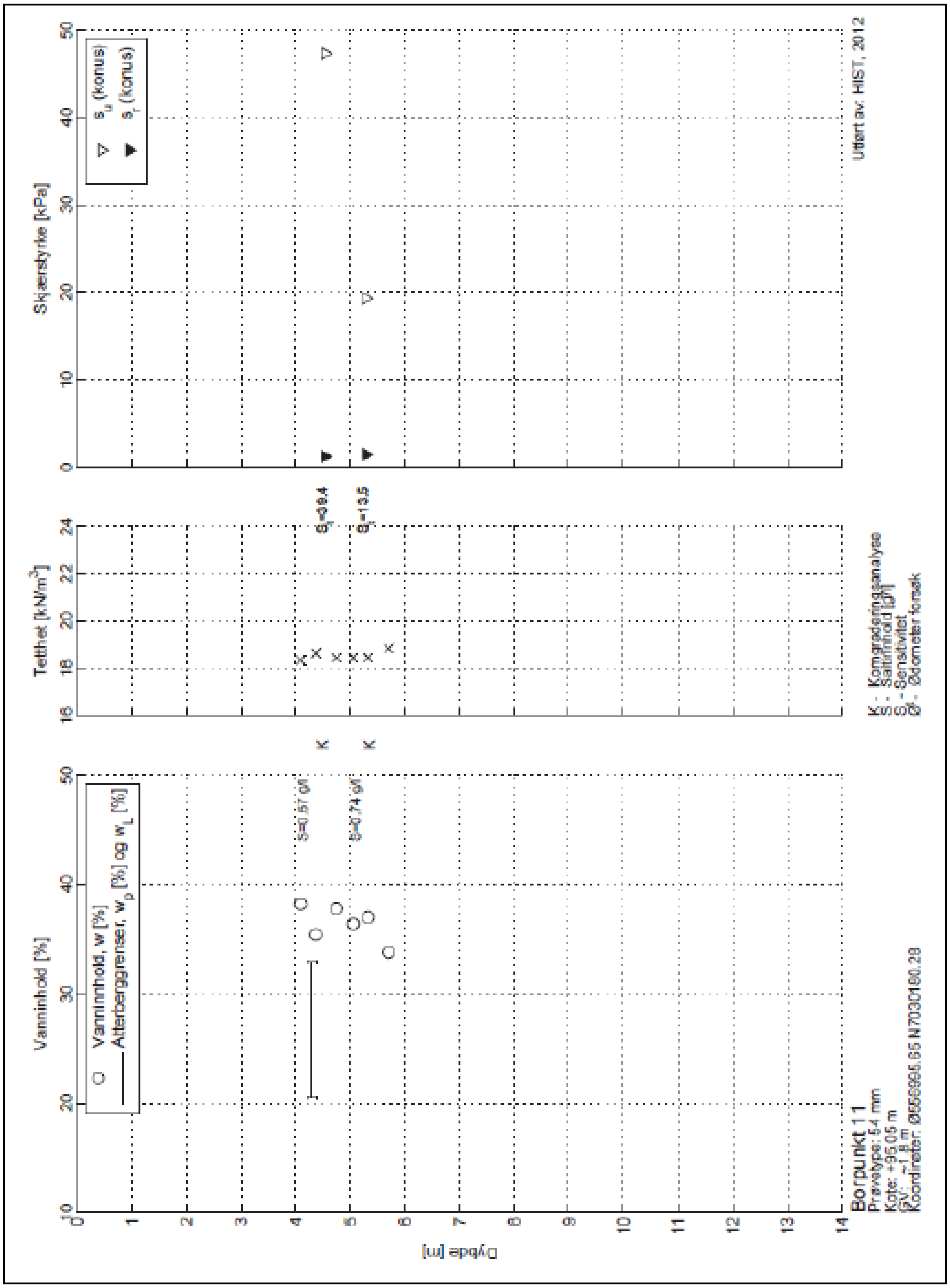
w(%)		Remolded		Intact			Uniaxial	
w	Depth	Cr	Depth	Ci	Depth	St=Ci/Cr	F	Depth
30.4094	9.16999	0.649351	9.20986	40.9091	9.20986	63	19.4805	9.16999
31.345	9.24973	0.649351	9.48895	44.1559	9.48895	68	55.1948	9.44908
36.0234	9.36934	0.649351	21.1707	33.7662	21.1707	52	39.6104	21.1707
32.7485	9.56869	0.649351	21.4897	33.7662	21.4897	52	39.6104	21.4498
33.2164	21.1308							
32.2807	21.3302							
31.345	21.5694							

Bore hole no. 118

w(%)		Remolded		Intact			Uniaxial	
w	Depth	Cr	Depth	Ci	Depth	St=Ci/Cr	F	Depth
34.0095	2.18807	3.87097	2.23269	36.129	2.23269	9.33	29.6774	2.19282
38.2435	2.38698	2.58065	2.51178	38.7097	2.51178	15.00	40	2.47191
36.3599	2.5859	2.58065	18.2204	38.7097	18.1805	15.00	20	18.1805
37.6718	18.1411	2.58065	18.4596	55.4839	18.4995	21.50	69.6774	18.4596
34.3769	18.2604	3.87097	21.1707	43.2258	21.2106	11.17	34.8387	21.1308
37.2	18.34	4.51613	21.4897	55.4839	21.4897	12.29	54.8387	21.4498
40.0222	18.5389							
32.9468	21.1248							
28.71	21.3635							
30.5911	21.5624							

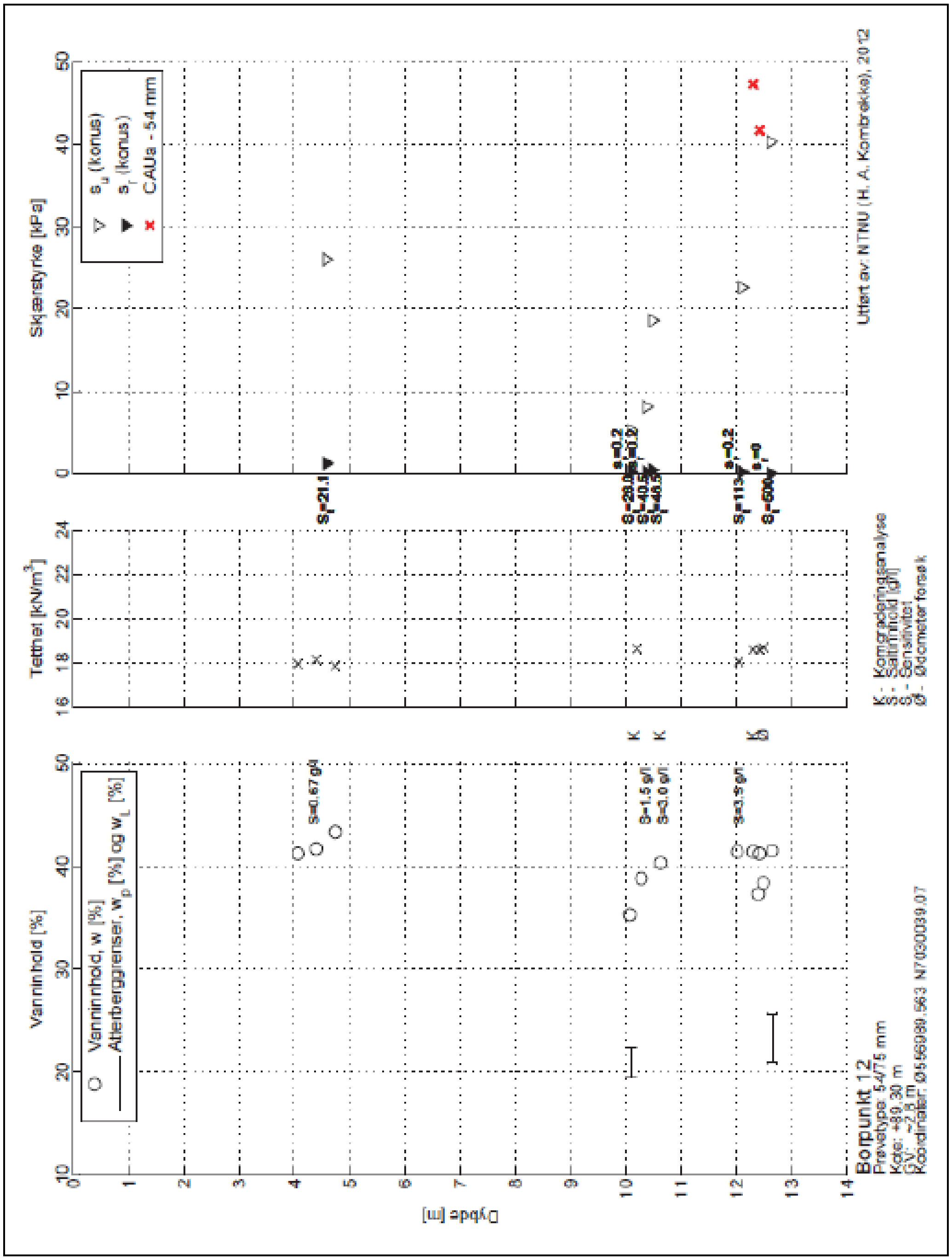
Byneset site

Bore-hole no. 11



Byneset site

Bore-hole no. 12



Byneset site

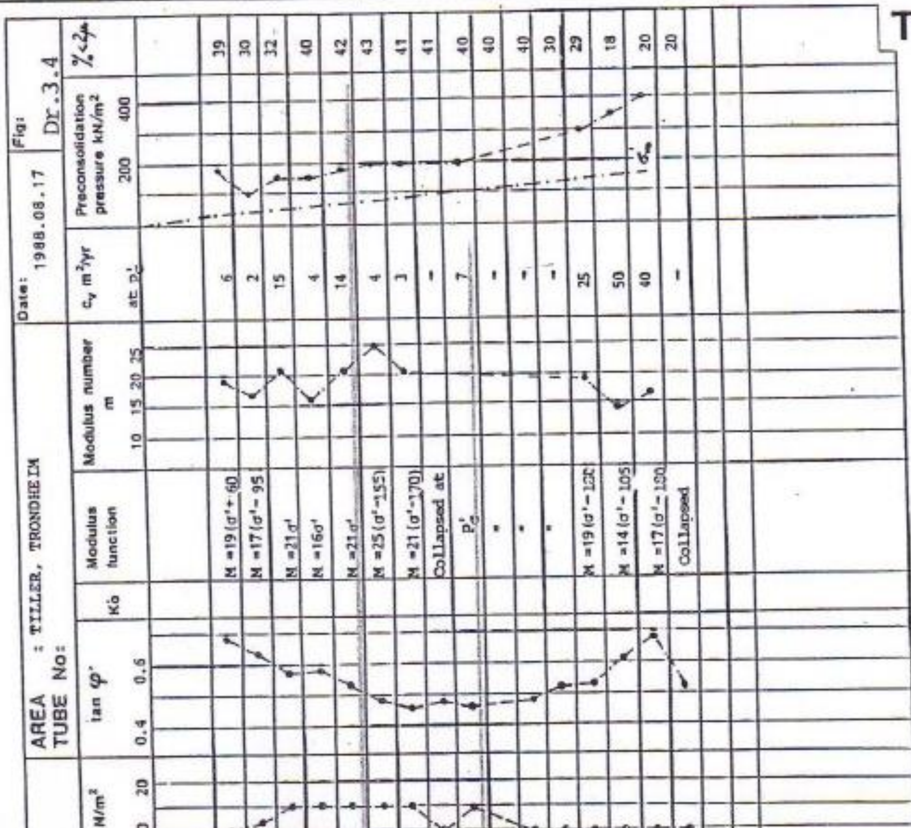
Bore hole 11, Laboratory data calculated

w(%)		Remolded		Intact		
w	Depth	Cr	Depth	Ci	Depth	St=Ci/Cr
38.31823	4.100307	1.154236	4.529097	47.15624	4.529097	40.85494
35.49849	4.3683	1.321516	5.306279	19.0532	5.27948	14.41768
37.91541	4.743492					
36.4384	5.065084					
37.10977	5.333078					
33.88721	5.70827					

Bore hole 12

w(%)		Remolded		Intact		
w	Depth	Cr	Depth	Ci	Depth	St=Ci/Cr
41.12782	4.084227	1.339117	4.638135	26.04677	4.638135	19.45071
41.57895	4.405819	0.207469	10.12151	8.129008	10.12151	39.1818
43.23308	4.754211	0.207469	10.389	18.69106	10.389	90.09086
35.41353	10.08729	0.584685	10.49599	22.65183	10.49599	38.74193
38.87218	10.27489	0.207469	12.12763	40.38099	12.12763	194.6363
40.22556	10.65008	0.207469	12.63584	22.5	12.63584	108.4499
41.57895	12.04364					
41.27819	12.28484					
41.12782	12.41884					
41.42857	12.63323					
37.21804	12.39204					
38.27068	12.49923					

TILLER



Boring profile, Tiller clay, Trondheim

PROJECT	Dr.ing.
DATE	1989.02.15
	Drawing 3.4

GEOTECHNICAL DIVISION
THE NORWEGIAN INSTITUTE OF TECHNOLOGY

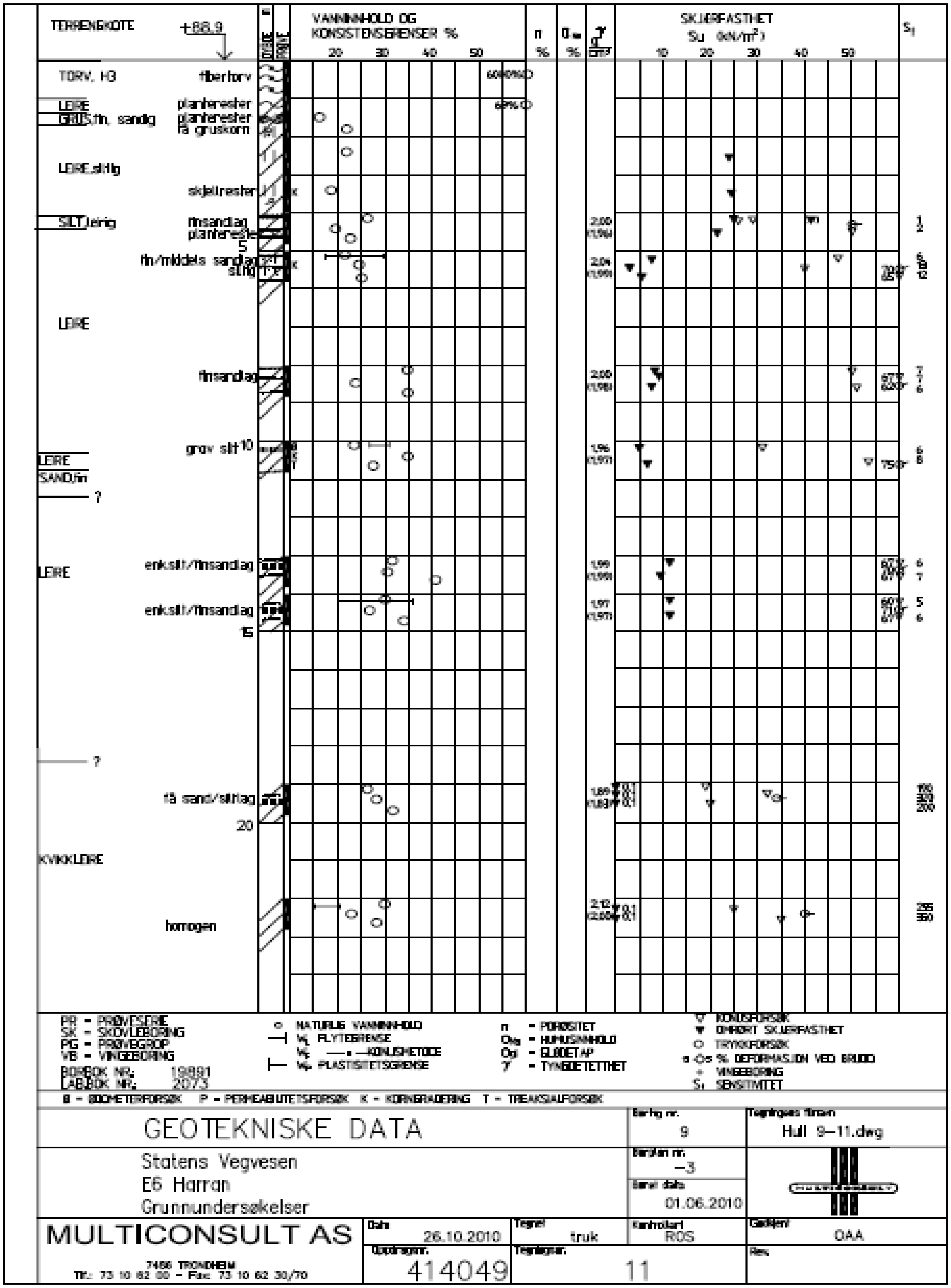
Tiller site

Laboratory data calculated

Water content		Remolded s.strenght		Intact s. strength		Sensitivity,
W(%)	Depth	Cr	Depth	Ci	Depth	St
28.60	1.80	0.64	17.36	40.76	17.36	64.16
25.17	1.98	0.69	16.42	36.44	16.42	52.79
31.62	1.96	0.75	16.27	37.93	16.27	50.89
36.48	2.49	0.43	14.67	37.35	14.67	86.40
41.01	2.71	0.48	14.16	31.52	14.16	65.19
37.58	2.80	0.16	13.64	24.57	13.64	151.17
37.56	3.05	0.21	13.30	29.03	13.30	135.86
37.13	3.42	0.63	12.72	32.40	12.72	51.20
32.19	3.53	0.32	12.20	24.72	12.20	78.27
31.41	3.78	0.37	10.76	21.55	10.76	58.12
30.60	4.21	0.41	10.25	21.24	10.25	51.28
29.06	4.42	0.57	9.75	22.39	9.75	39.46
31.31	4.64	0.62	9.32	21.33	9.32	34.49
28.99	4.98	0.30	8.84	14.75	8.84	48.92
30.49	5.14	0.71	8.28	24.75	8.28	34.72
30.47	5.35	0.03	7.76	16.33	7.76	514.19
34.21	5.73	0.09	7.30	20.06	7.30	221.14
31.92	5.91	0.51	6.77	27.48	6.77	53.89
32.64	6.22	1.66	6.26	24.22	6.26	14.58
34.87	6.56	2.08	5.79	19.48	5.79	9.38
41.30	6.72	2.13	5.24	18.43	5.24	8.65
39.00	6.94	4.01	4.77	15.17	4.77	3.78
42.36	7.37	2.60	4.23	20.37	4.23	7.84
40.06	7.62	1.91	3.69	18.59	3.69	9.72
42.70	7.74	1.96	3.22	19.00	3.22	9.70
33.93	8.13	2.75	2.71	18.32	2.71	6.65
38.08	8.32	2.43	2.17	38.99	2.17	16.02
34.27	8.53	5.44	2.69			
37.55	9.68	5.48	2.22			
41.32	9.87					
42.04	10.15					
43.14	10.52					
41.60	10.70					
33.61	10.97					
38.87	11.35					
39.98	11.57					
37.31	11.75					
37.26	12.15					
40.28	12.31					
39.86	12.58					
37.55	12.92					
32.98	13.13					
32.57	13.34					
31.01	13.77					
35.91	13.96					
30.96	14.20					

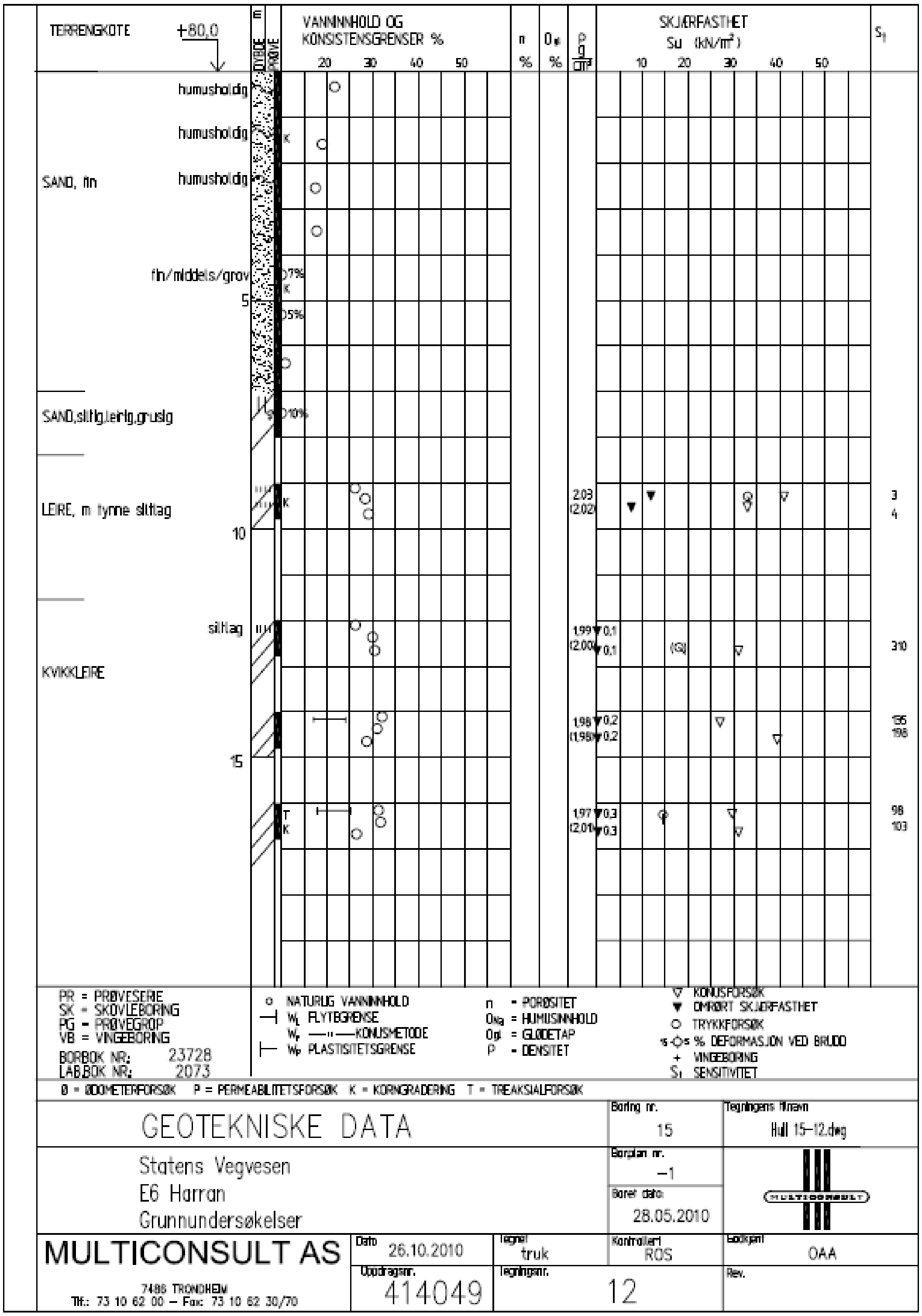
Harran site

Bore hole no.9



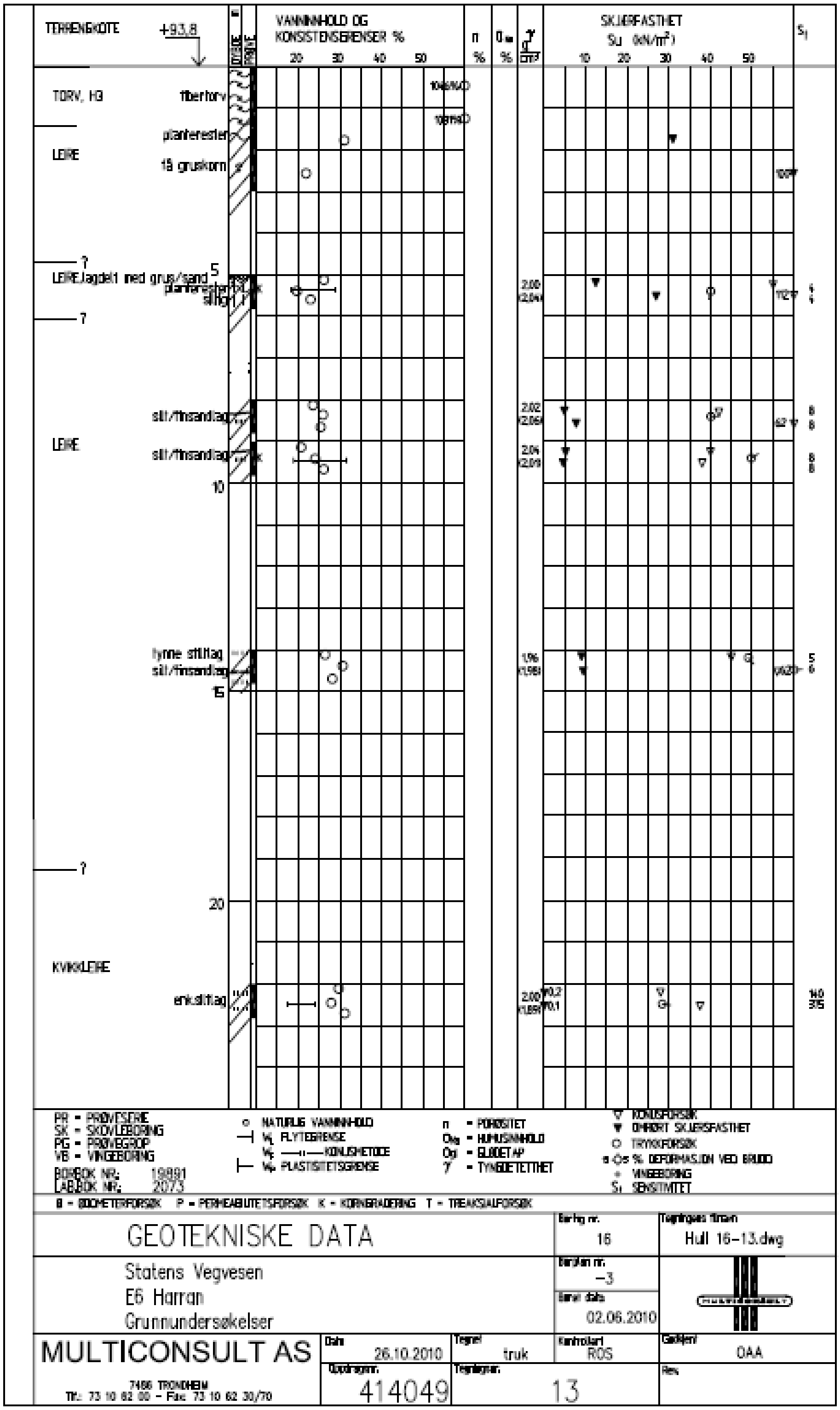
Harran site

Bore hole no.15



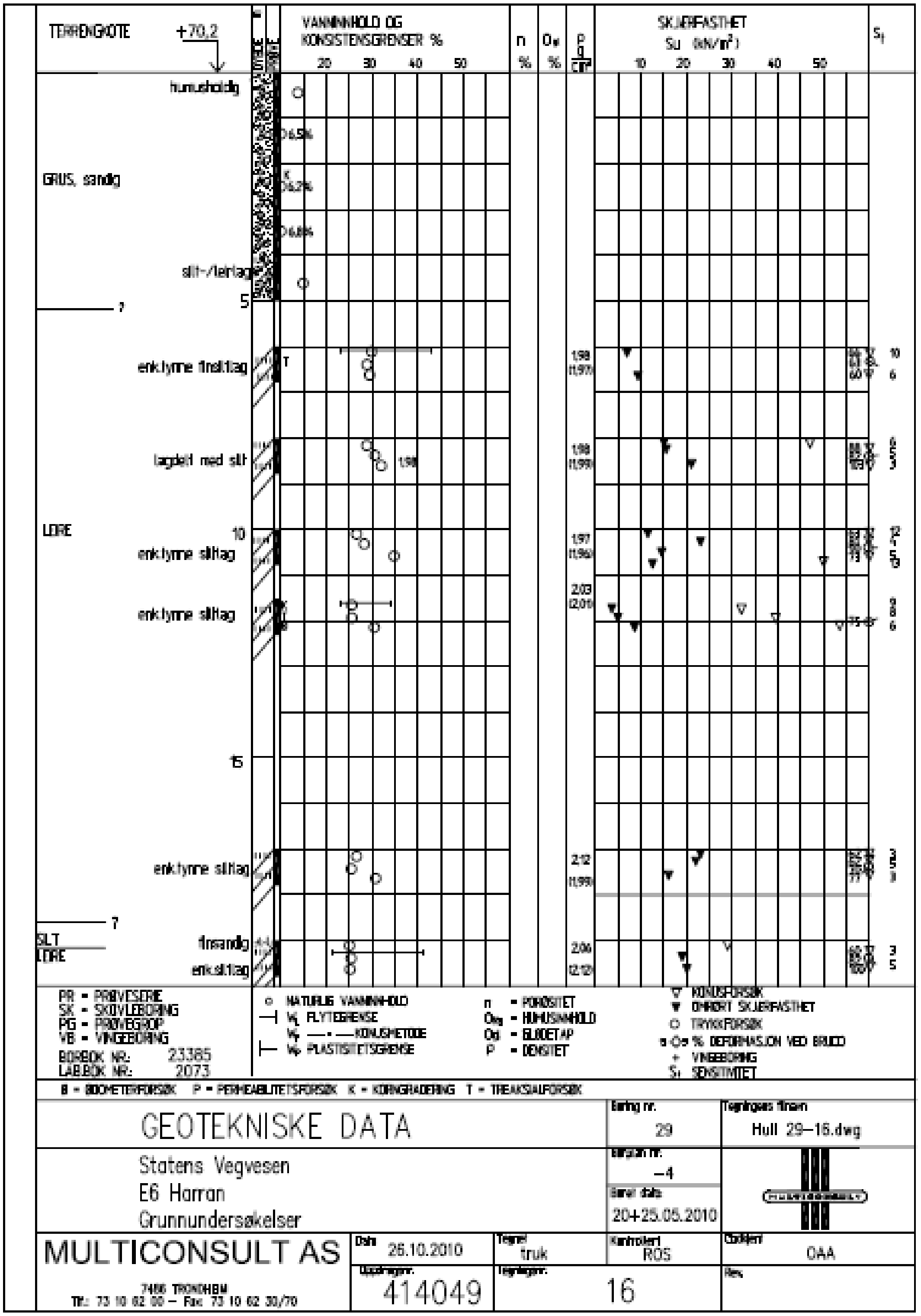
Harran site

Bore hole no.16



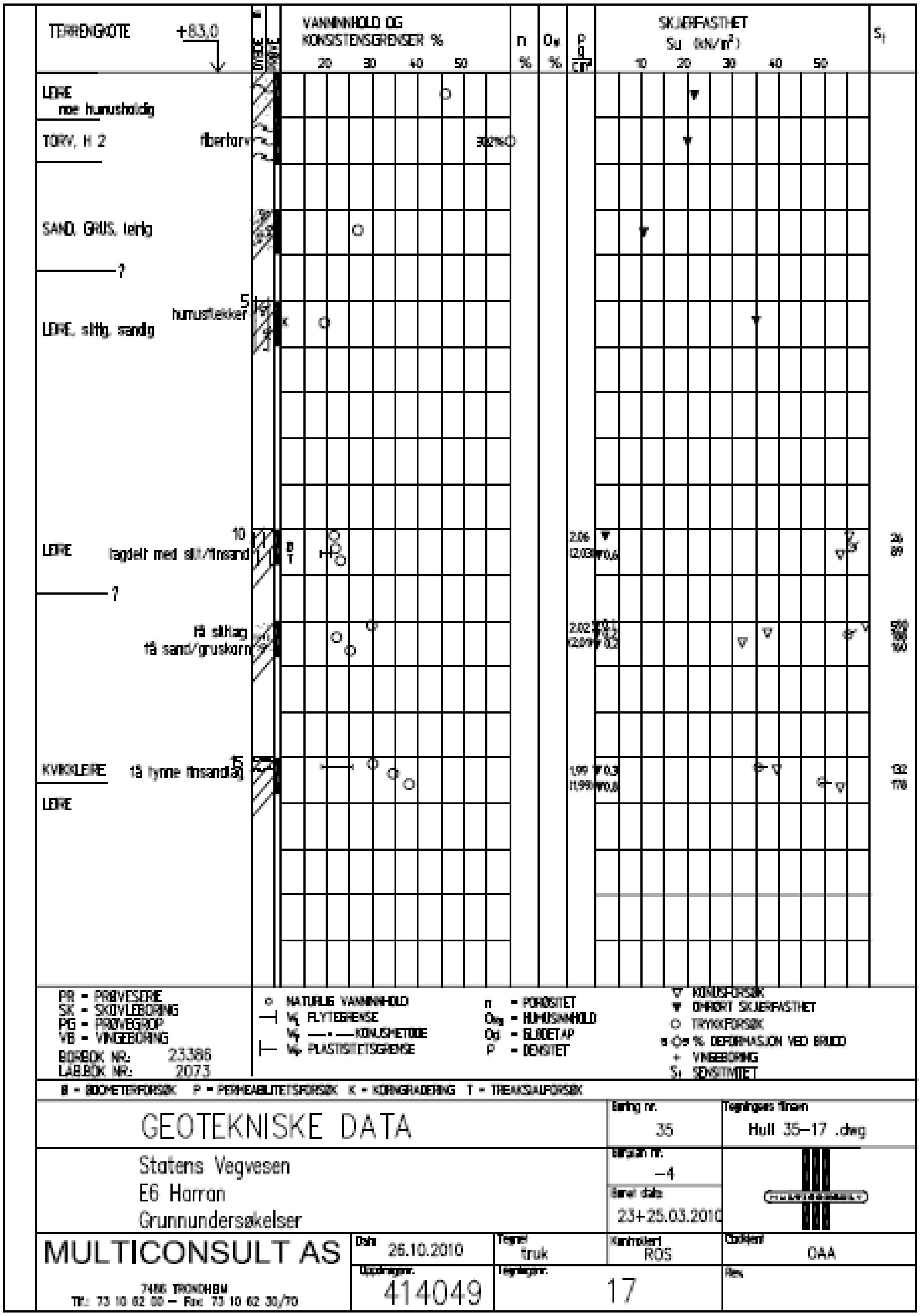
Harran site

Bore hole no.29



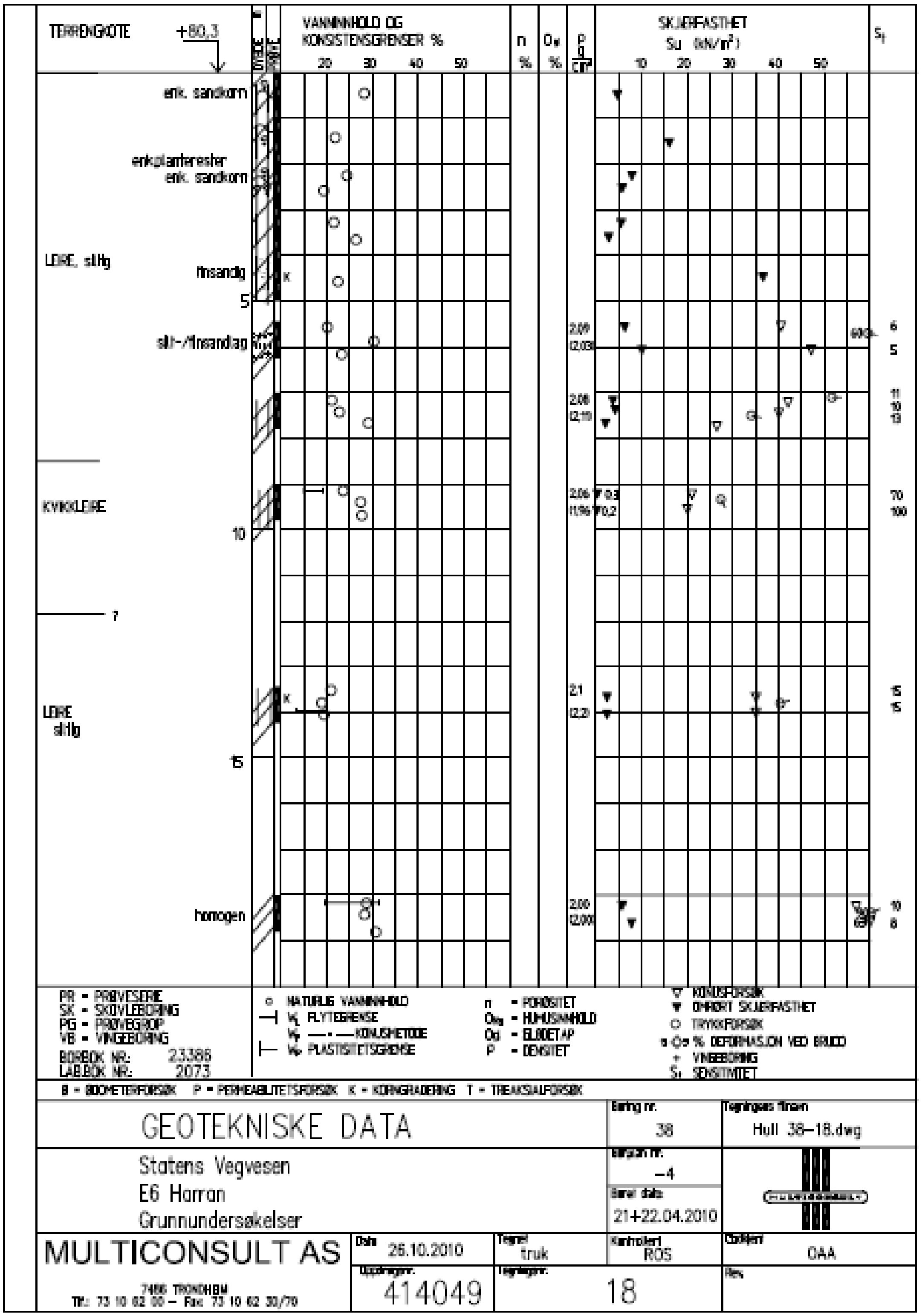
Harran site

Bore hole no.35



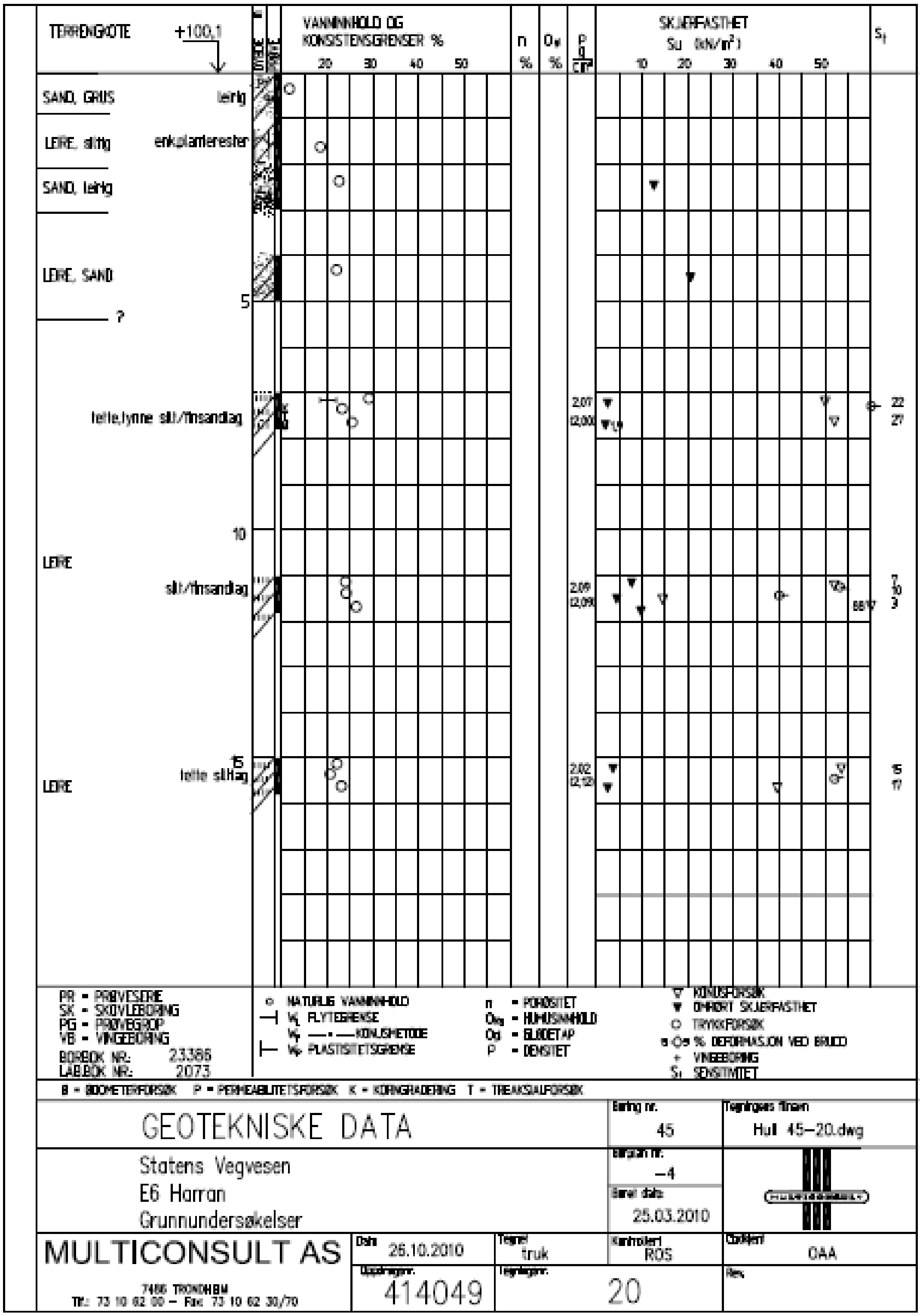
Harran site

Bore hole no.38



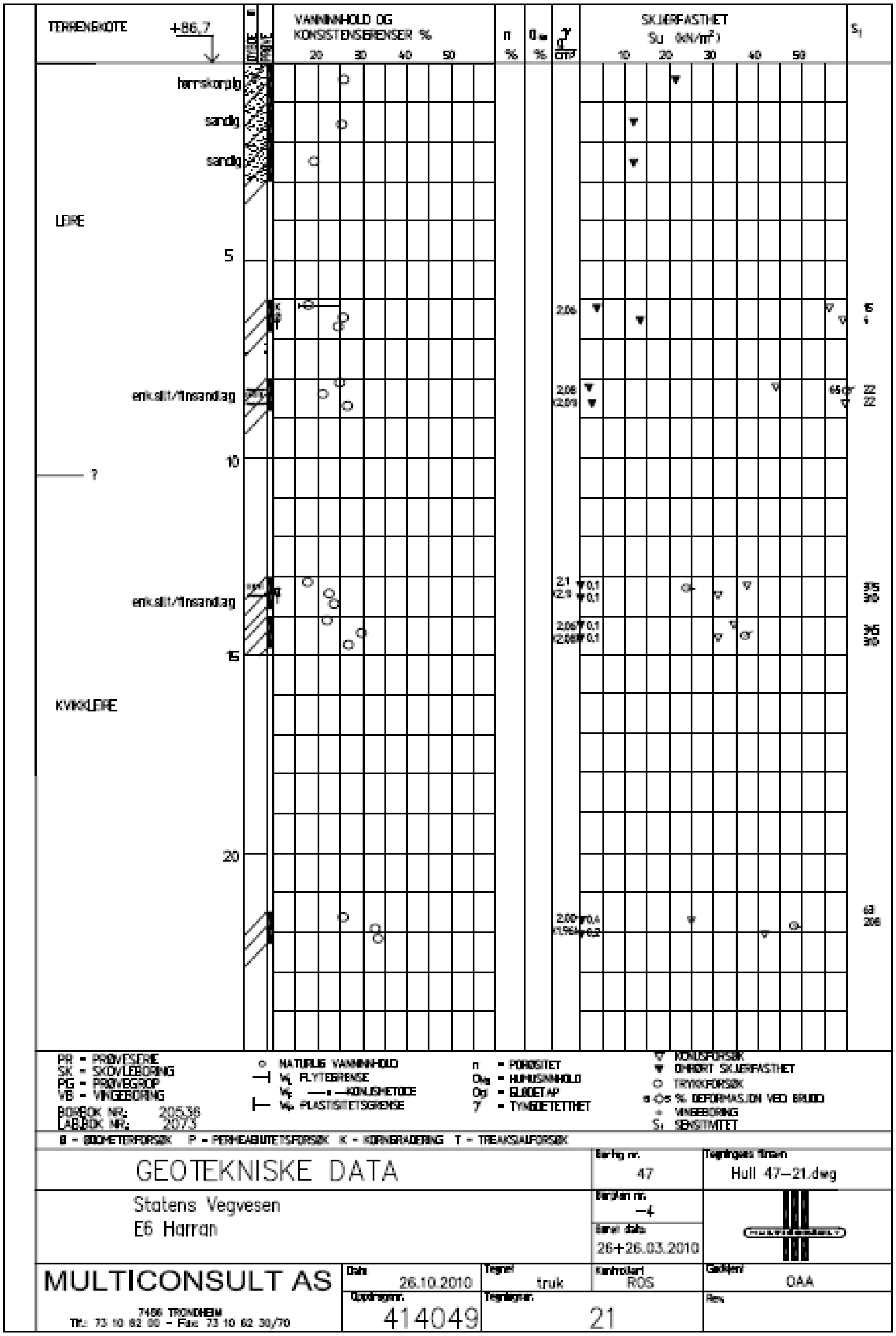
Harran site

Bore hole no.45



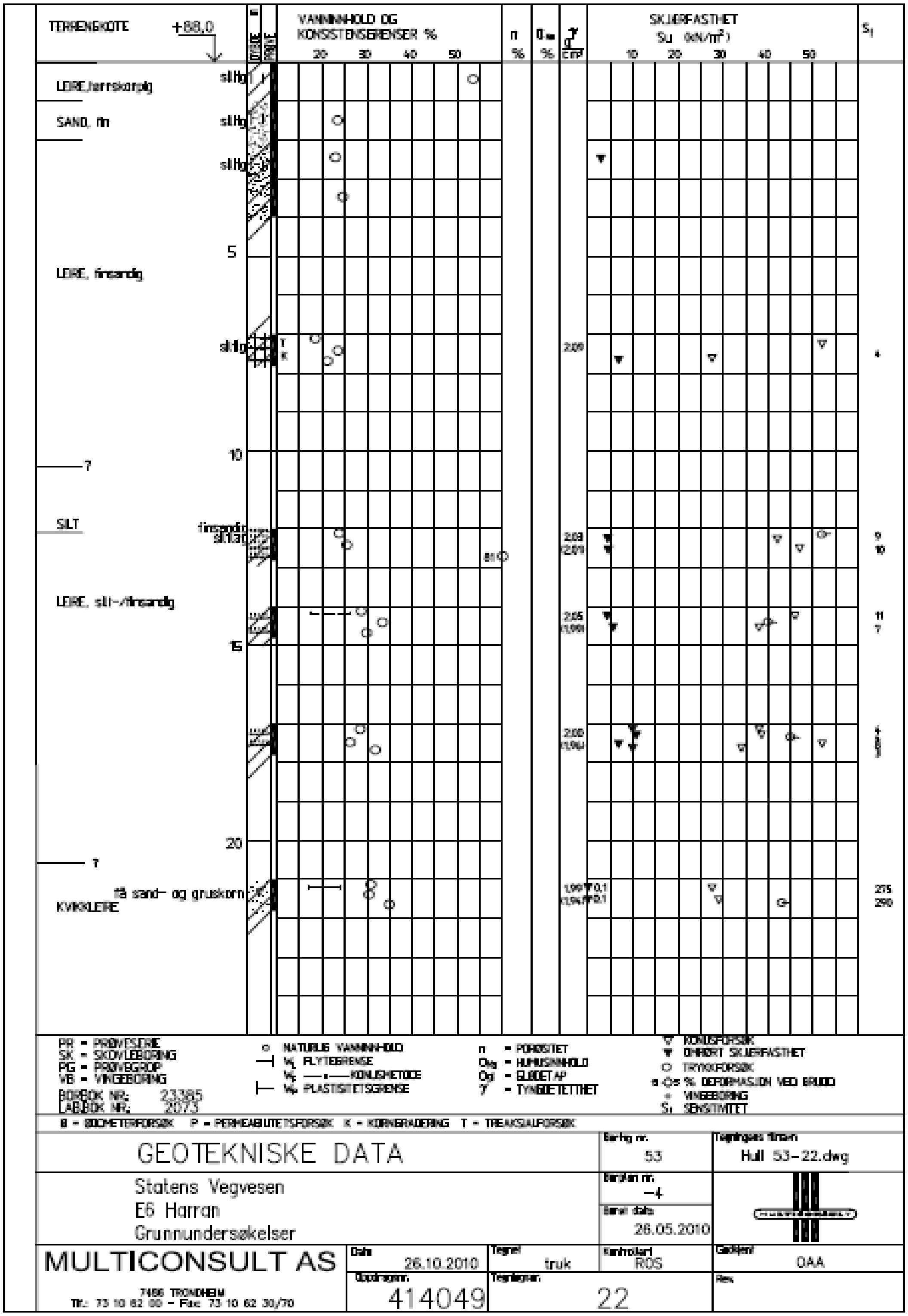
Harran site

Bore hole no.47



Harran site

Bore hole no.53



Harran site

Bore hole no. 9,15,1629,35,38,45,47,53, Laboratory data calculated

BH9					
w(%)		Remolded		Intact	
w	Depth	Cr	Depth	Ci	Depth
7.317073	1.473648	23.62	2.48	28.86297	4.14355
14.84321	1.75104	24.31	3.45	49.85423	4.420943
14.42509	2.375173	24.66	4.11	47.05539	5.149098
10.66202	3.415395	21.17	4.42	40.05831	5.357143
19.44251	4.108877	7.17	5.18	59.30029	5.634535
59.58188	0.2947295	2.27	5.39	49.85423	8.096394
59.58188	1.092233	4.72	5.60	50.90379	8.512483
11.49826	4.386269	8.22	8.10	59.65015	8.269764
15.67944	4.628987	8.92	8.24	30.61225	10.10749
13.58885	5.114424	7.17	8.48	53.70263	10.4889
17.35192	5.322469	4.72	10.11	59.65015	13.12413
18.18815	5.634535	6.47	10.52	59.65015	13.47087
29.47735	8.096394	11.02	13.12	59.65015	14.16436
16.51568	8.443134	9.27	13.47	59.30029	14.54577
29.89547	8.685853	11.02	14.10	18.7172	19.01872
16.51568	10.10749	11.02	14.51	32.01166	19.19209
21.5331	10.55825	0.17	18.98	19.76676	19.43481
29.47735	10.38488	0.17	19.23	24.66472	22.24341
25.71428	13.12413	0.17	19.43	34.8105	22.52081
24.87805	13.40153	0.17	22.17		
37.00348	13.64424	0.17	22.49		
24.04181	14.16436				
19.86063	14.40707				
29.05923	14.64979				
19.02439	19.08807				
21.95122	19.36547				
26.1324	19.64286				
24.04181	22.13939				
15.67944	22.41678				
21.95122	22.62483				

BH15					
w(%)		Remolded		Intact	
w	Depth	Cr	Depth	Ci	Depth
13.64486	0.373026	11.88	9.31	40.87403	9.278034
9.906542	1.603783	7.56	9.52	32.85347	9.493088
8.411215	2.55798	0.77	12.20	31.00257	12.62673
8.785047	3.481863	0.77	12.63	26.99229	14.19355
1.308411	4.465318	0.77	14.16	39.33162	14.59293
1.308411	6.405272	0.46	14.53	29.15167	16.2212
1.308411	7.513817	0.77	16.19	30.69409	16.58986
19.25234	9.119653	0.77	16.59		
21.86916	9.366669				
22.61682	9.674789				
18.8785	12.10647				
23.73832	12.38485				
24.11215	12.63129				
26.35514	14.10993				
24.48598	14.38659				
21.86916	14.69384				
25.23364	16.17277				
25.98131	16.45009				
19.25234	16.66392				

BH16					
w(%)		Remolded		Intact	
w	Depth	Cr	Depth	Ci	Depth
25.05263	1.77575	31.13	1.70	55.13044	5.166436
13.68421	2.535295	12.35	5.10	59.65217	5.443828
19.57895	5.102878	60.00	2.50	41.91304	8.217753
11.57895	5.377959	26.61	5.44	59.65217	8.529819
15.36842	5.552425	5.04	8.18	40.17391	9.153953
15.78947	8.083753	7.83	8.50	38.08696	9.431345
19.15789	8.327445	5.39	9.15	45.04348	14.07767
18.73684	8.604715	4.70	9.47	56.17391	14.45908
12.8421	9.123123	9.22	14.15	28	22.15673
16.21053	9.366815	9.22	14.46	37.3913	22.46879
19.57895	9.645181	0.87	22.19		
19.15789	14.08334	0.87	22.54		
24.63158	14.36231				
21.26316	14.67341				
23.78947	22.12906				
21.26316	22.40572				
25.47368	22.71901				

BH29					
w(%)		Remolded		Intact	
w	Depth	Cr	Depth	Ci	Depth
4.444445	0.4157044	7.08	6.08	60	6.112394
1.481481	1.339492	9.54	6.57	60	6.574288
0.3703704	2.47883	15.08	8.05	47.07692	8.083141
0.3703704	3.43341	15.69	8.21	60	8.17552
5.925926	4.603541	20.92	8.55	60.30769	8.545034
23.7037	6.112394	11.69	10.05	56.61538	8.360277
22.22222	6.358737	23.08	10.21	59.69231	10.0231
23.33333	6.635874	14.46	10.45	59.69231	10.17706
22.22222	8.17552	12.31	10.70	59.69231	10.51578
24.07407	8.329484	3.69	11.69	49.84615	10.63895
26.2963	8.606621	4.92	11.84	32	11.68591
20	10.08468	8.62	12.09	39.38462	11.90146
21.11111	10.33102	23.08	17.04	53.53846	12.05543
29.62963	10.57737	22.15	17.20	59.69231	17.04388
18.51852	11.65512	16.00	17.51	59.69231	17.16705
18.51852	11.90146	19.08	19.29	59.69231	17.50577
24.44444	12.11701	20.31	19.57	28.92308	19.04542
20	17.13626			60	19.16859
18.14815	17.41339			56.92308	19.38414
24.81482	17.62894			60	19.53811
18.14815	19.10701				
18.14815	19.38414				
18.14815	19.63049				

BH38					
w(%)		Remolded		Intact	
w	Depth	Cr	Depth	Ci	Depth
43.17757	0.432169	21.44	0.46	55.37275	10.1251
59.25233	1.450853	19.90	1.48	53.21337	10.5264
20.37383	3.426482	10.03	3.46	58.76607	12.10073
10.65421	5.432981	34.70	5.43	37.17224	12.22421
13.64486	10.1251	2.01	10.13	31.92802	12.44029
13.64486	10.40292	0.15	10.56	39.33162	15.24939
15.14019	10.68075	0.15	12.07	53.21337	15.65069
23.73832	12.10073	-0.15	12.26		
14.39252	12.34768	-0.15	12.50		
17.75701	12.62551	0.15	15.28		
24.11215	15.12591	0.46	15.62		
29.34579	15.342				
33.45794	15.55808				

BH35					
w(%)		Remolded		Intact	
w	Depth	Cr	Depth	Ci	Depth
25.8125	0.4167344	4.64	0.42	40.51546	5.479285
16.1875	1.37368	15.77	1.47	47.01031	6.004062
20.125	2.207149	7.73	2.18	42.06186	7.177092
12.6875	2.54671	5.57	2.45	39.89691	7.393176
16.1875	3.225833	5.57	3.19	25.97938	7.701869
23.1875	3.658002	2.47	3.57	20.41237	9.152721
17.5	4.553209	36.49	4.40	19.48454	9.492283
14.4375	5.541024	6.49	5.51	34.63918	13.62876
28.875	5.880585	9.90	6.03	34.94845	13.96832
18.375	6.127539	3.40	7.12	56.90722	18.22827
15.75	7.146223	4.02	7.33	59.69072	18.53696
17.9375	7.393176	1.86	7.61		
27.125	7.64013	0.10	9.15		
18.8125	9.152721	0.10	9.55		
24.9375	9.368806	2.16	13.63		
24.9375	9.677498	2.16	14.00		
14.875	13.50528	5.57	18.20		
12.25	13.7831	7.42	18.57		
13.125	14.03006				
26.25	18.16653				
25.375	18.41348				
29.3125	18.78391				

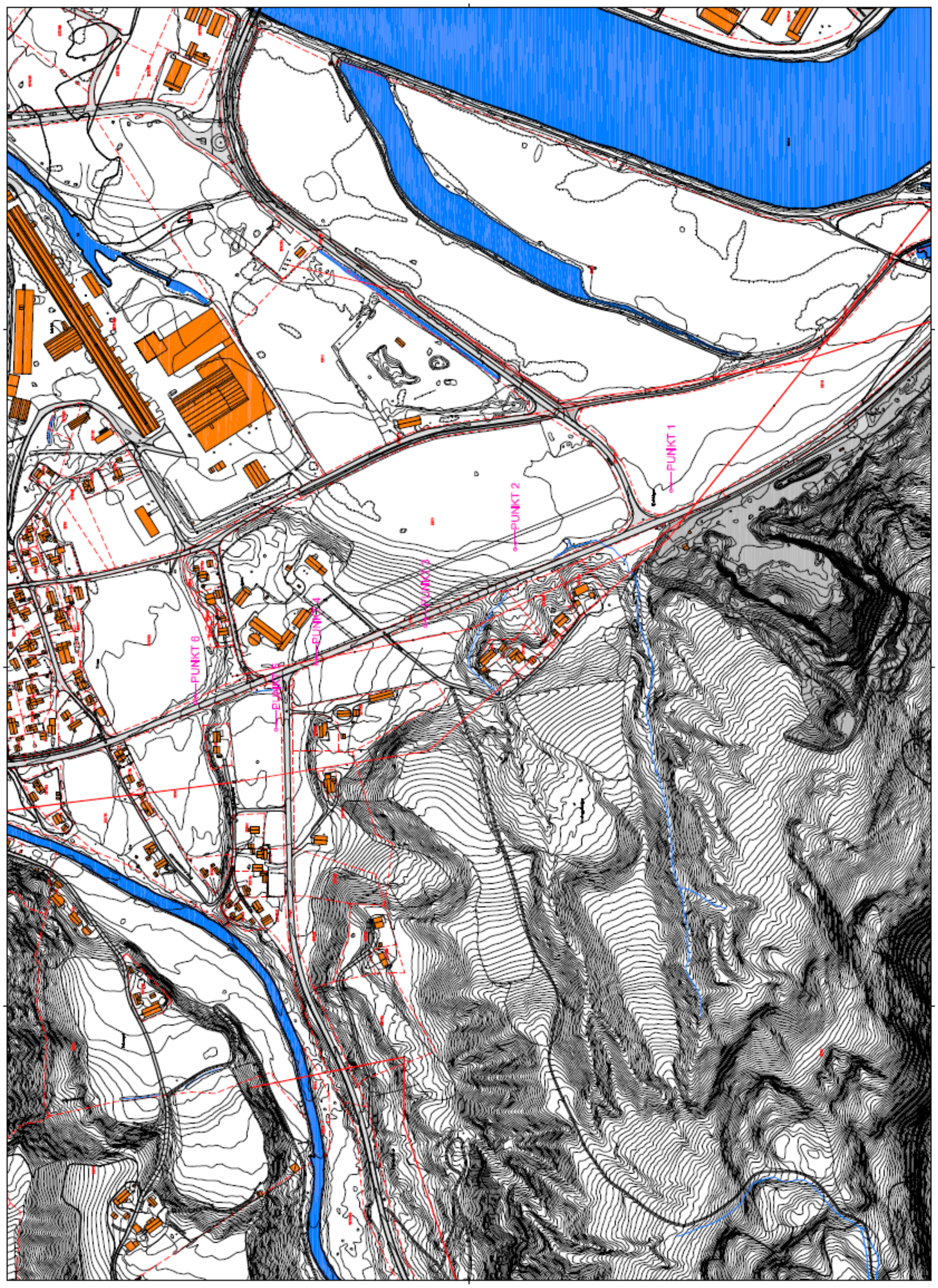
BH45					
w(%)		Remolded		Intact	
w	Depth	Cr	Depth	Ci	Depth
2.160494	0.3461539	12.31	2.28	49.53846	6.721154
11.66667	1.528846	20.31	4.18	51.69231	7.125
17.28395	2.221154	2.15	6.75	51.69231	10.5
16.85185	4.067307	1.54	7.21	59.38462	10.90385
26.79012	6.692307	7.69	10.44	14.15385	10.78846
18.14815	6.923077	4.00	10.76	53.23077	14.25
21.60494	7.182693	9.54	11.02	39.07692	14.65385
19.44444	10.44231	3.38	14.25		
19.44444	10.67308	2.15	14.63		
22.46914	10.96154				
16.41975	14.19231				
14.69136	14.36539				
18.14815	14.65385				

BH47					
w(%)		Remolded		Intact	
w	Depth	Cr	Depth	Ci	Depth
2.160494	0.3461539	21.17	0.35	56.1516	6.137309
11.66667	1.528846	11.72	1.42	59.30029	6.414702
17.28395	2.221154	11.72	2.46	43.9067	8.113731
16.85185	4.067307	3.32	6.14	59.65015	8.564494
26.79012	6.692307	13.47	6.45	37.60933	13.17614
18.14815	6.923077	1.57	8.15	30.61225	13.41886
21.60494	7.182693	1.92	8.53	34.46064	14.14702
19.44444	10.44231	-0.17	13.14	30.9621	14.49376
19.44444	10.67308	-0.17	13.45	24.66472	21.67129
22.46914	10.96154	0.52	14.08	41.45773	22.01803
16.41975	14.19231	0.52	14.46		
14.69136	14.36539	0.17	21.67		
18.14815	14.65385	0.17	21.98		

BH53					
w(%)		Remolded		Intact	
w	Depth	Cr	Depth	Ci	Depth
52.47387	0.4507628	2.96	2.46	52	7.246879
16.09756	1.490985	6.78	7.59	27.65217	7.558946
15.67944	2.427185	4.35	12.24	41.91304	12.23994
17.35192	3.432732	4.35	12.48	47.13044	12.48266
9.825784	7.108183	4.00	14.18	46.08696	14.18169
16.09756	7.420249	5.39	14.49	38.08696	14.52843
13.58885	7.662968	9.91	17.09	38.08696	17.09431
16.51568	12.13592	10.61	17.23	38.78261	17.26768
18.60627	12.37864	9.91	17.58	33.91304	17.57975
59.58188	12.72538	6.78	17.51	52.34783	17.5104
22.36934	14.11234	1.22	21.22	27.30435	21.18585
28.223	14.38974	0.87	21.57	29.04348	21.53259
24.04181	14.66713				
21.95122	17.16366				
19.02439	17.47573				
26.55052	17.68377				
24.87805	21.15118				
24.87805	21.3939				
29.89547	21.63662				

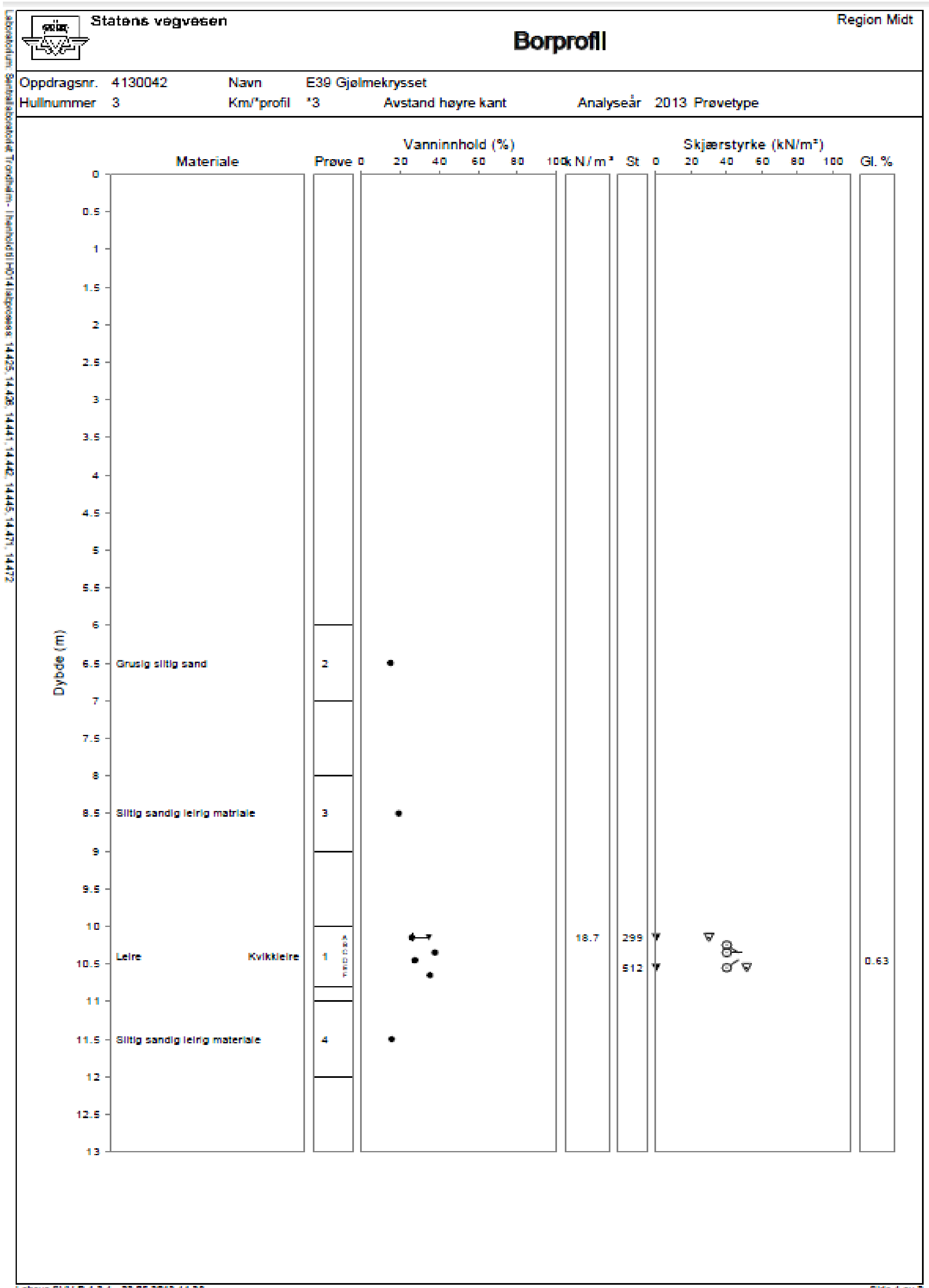
E39 Road project

Bore plan



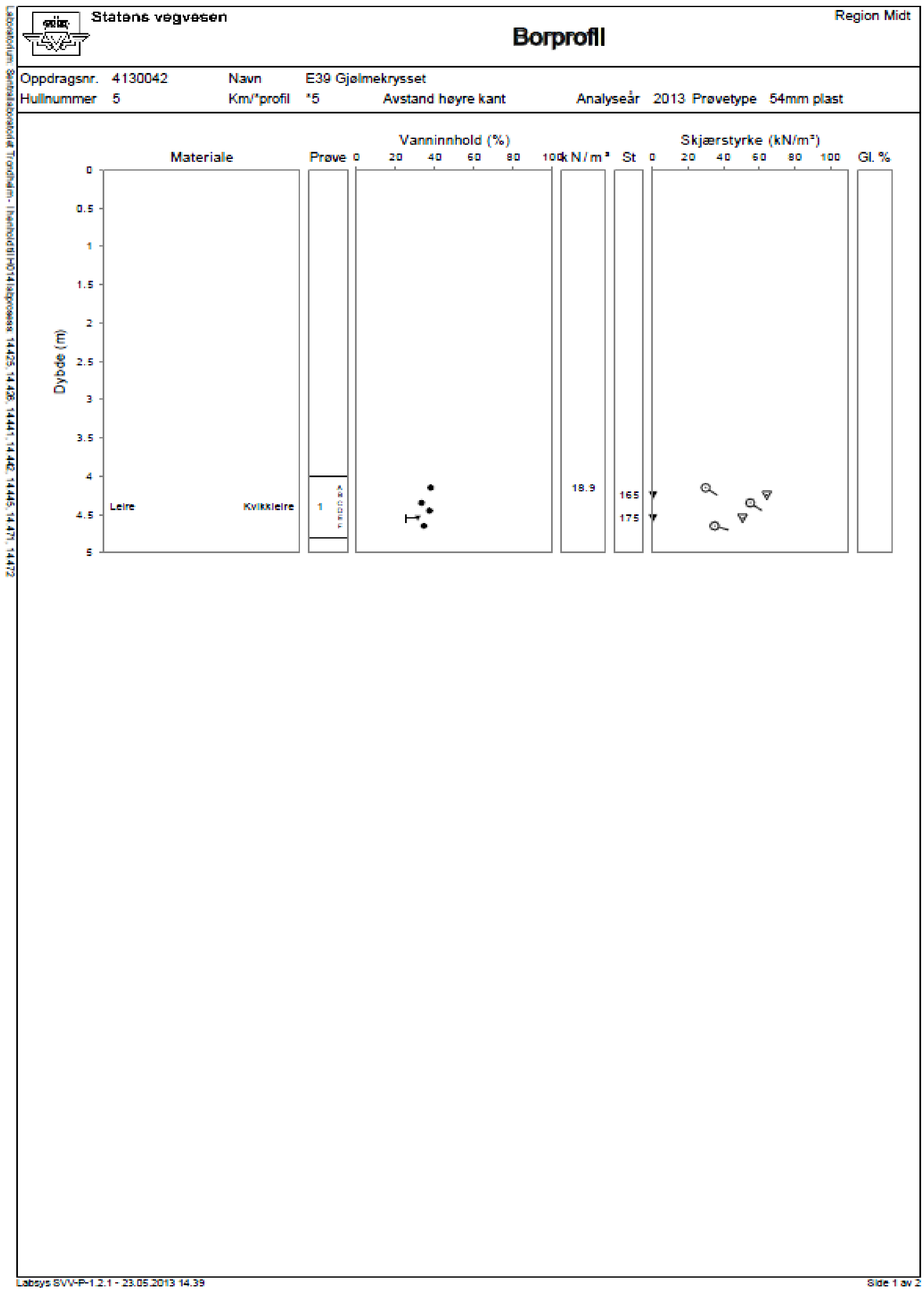
E39 Road project

Bore Hole no. 3



E39 Road project

Bore Hole no. 5



E39 Road project

Bore hole no. 3 , Grain size distribution

Laboratorium: Sentrallaboratoriet Trondheim - i henhold til H014 labprosess 14432, 14433, 14434

Statens vegvesen

Region Midt

Kornkurve

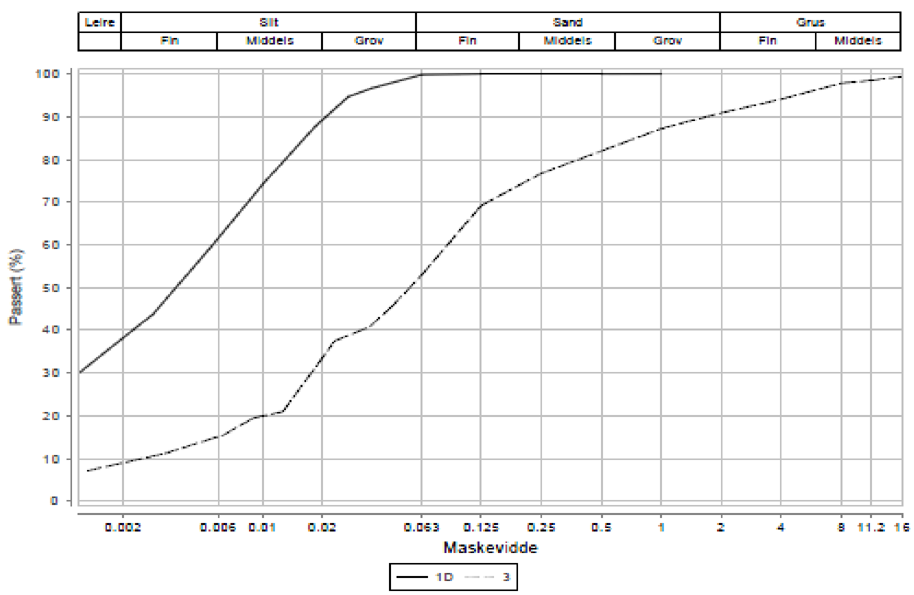
Oppdragsnr.	**4130042**	Oppdragsnavn	**E39 Gjølmekrysset**
Prosjektnr.	**404328**	Prosjektnavn	**E39 Kryssløsning Gjølme**
Ansvarsområdenr.	**45220**	Ansvarsområdenavn	**ST Utbyggingsseksjonen**

Serienr. 3, Hullnr. 3

Sylinder / Pose nr.	1D	3			
Uttaksdato	02.04.2013	02.04.2013			
Uttatt kl.					
Analysetype	Våtsikt	Våtsikt			
Humus (Glødetap)	0.6				
Vanninnhold (%)	27.4	19.1			
% <63µm av <delsikt	99.8 (20 mm)	52.9 (20 mm)			
% <20µm av <delsikt	89.1 (20 mm)	33.5 (20 mm)			

Siktedata - Passert (%)

	µm				mm					
Pr.nr.	**63**	**125**	**250**	**500**	**1**	**2**	**4**	**8**	**11.2**	**16**
1D	99.8	100.0	100.0	100.0	100.0					
3	52.9	69.1	76.7	81.9	87.1	90.9	94.1	97.8	98.4	99.3



Syl/pose	**Vegnr**	**HP**	**Km/profil**	**Avst.cl**	**Dybde**	**Jordart**	**Cu**	**TG**
1D	EV39		*3		10.0 - 10.8	Leire	0.0	T4
3	EV39		*3		8.0 - 9.0	Siltig sandig leirig matriale	34.0	T4

Sted:____________________ Dato:_________ Signatur:____________________

E39 Road project

Bore hole no. 5 , Grain size distribution

Laboratorium: Sentrallaboratoriet Trondheim - I henhold til H014 labprosess 14432, 14433, 14434

Statens vegvesen

Region Midt

Kornkurve

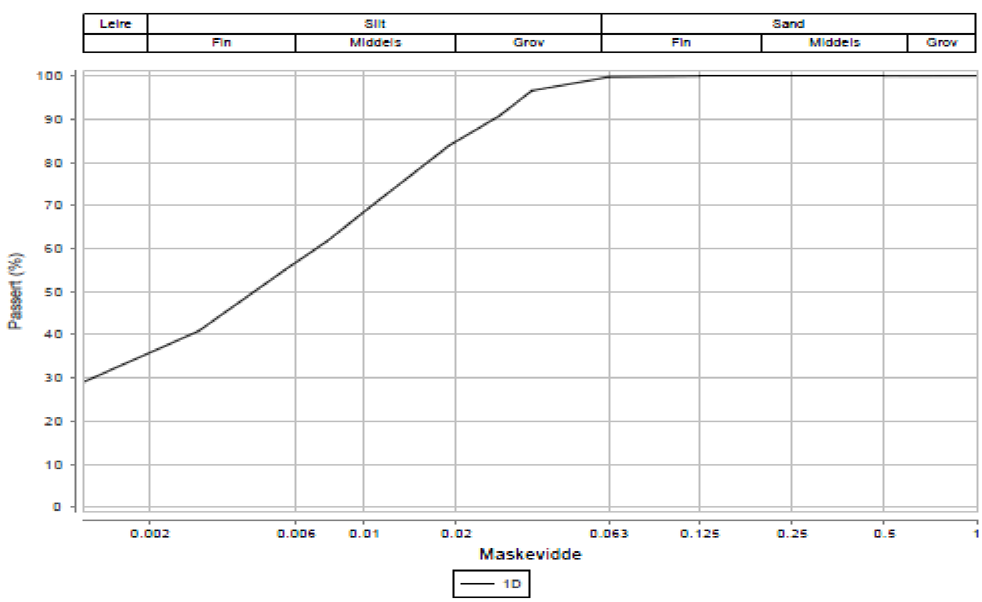
Oppdragsnr.	**4130042**	Oppdragsnavn	**E39 Gjølmekrysset**
Prosjektnr.	**404328**	Prosjektnavn	**E39 Kryssløsning Gjølme**
Ansvarsområdenr.	**45220**	Ansvarsområdenavn	**ST Utbyggingsseksjonen**

Serienr. 5, Hullnr. 5

Sylinder / Pose nr.	1D				
Uttaksdato	02.04.2013				
Uttatt kl.					
Analysetype	Våtsikt				
Humus (Glødetap)					
Vanninnhold (%)	37.3				
% <63µm av <delsikt	99.7 (20 mm)				
% <20µm av <delsikt	84.8 (20 mm)				

Siktedata – Passert (%)

	µm				mm
Pr.nr.	**63**	**125**	**250**	**500**	**1**
1D	99.7	99.9	99.9	99.9	100.0



Syl/pose	Vegnr	HP	Km/*profil	Avst.cl	Dybde	Jordart	Cu	TG
1D	EV39		*5		4.0 - 4.8	Leire	0.0	T4

Sted:____________________ Dato:_________ Signatur:____________________

Lab-calculated

BH-3

w(%)		Remolded		Intact		St
w	Depth	Cr	Depth	Ci	Depth	
15.32258	6.48	0.11	10.12	33.6	10.12	305.45
19.35484	8.48	0.11	10.52	56.64	10.52	514.91
25.80645	10.14					
37.90322	10.33					
27.41936	10.43					
35.48387	10.64					
16.12903	11.48					

Lab calculated

BH-5

w(%)		Remolded		Intact		St
w	Depth	Cr	Depth	Ci	Depth	
37.91	4.15	0.42	4.24	69.38	4.24	165.20
33.18	4.36	0.31	4.54	55.17	4.54	177.95
36.97	4.45					
34.60	4.65					