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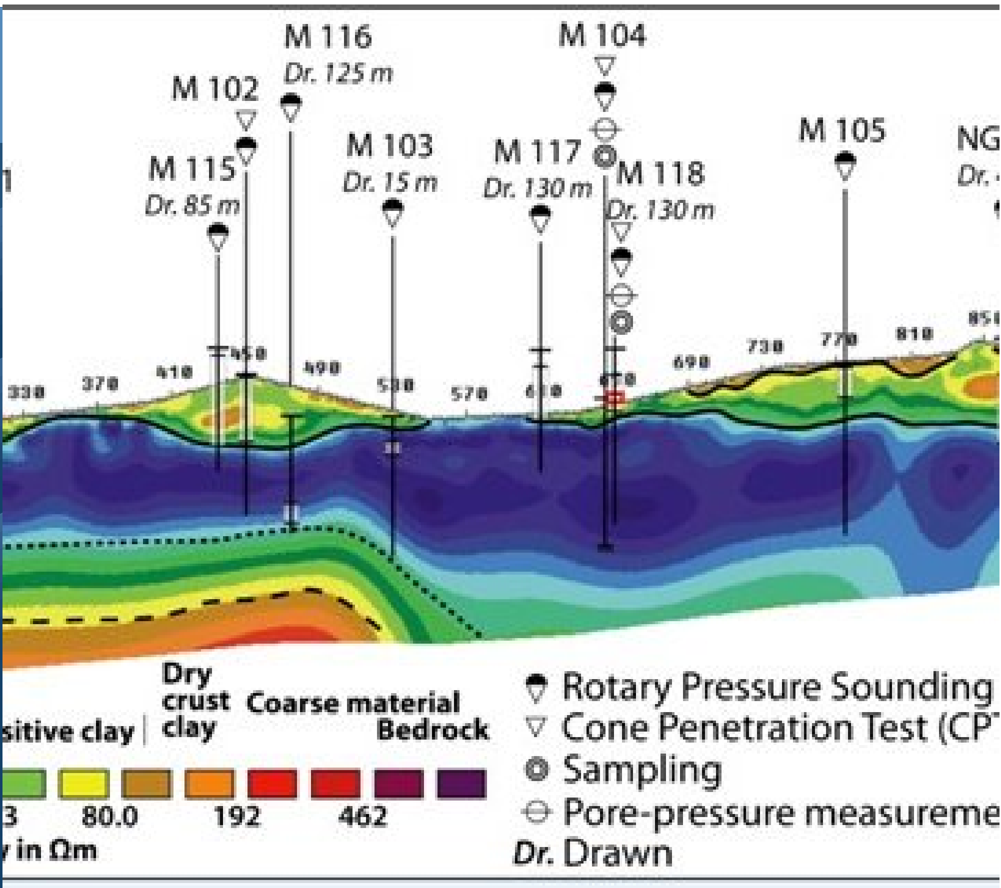
Detection of brittle materials. Summary report with recommendation

Natural hazards –infrastructure for floods and slides. Sub project 6 Quick clays

27
2016

RAPPORT



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NATURFARE
INFRASTRUKTUR - FLOM - SKRED

Rapport nr 27-2016

Detection of brittle materials. Summary report with recommendation

Utgitt av: Norges vassdrags- og energidirektorat

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Sammendrag: This report concludes a study on “Detection of brittle materials”, carried out between 2012 and 2015. This report recommend methods and procedures for detection of brittle materials from various field and laboratory tests. The report is based on previous work in this study, where various new and existing detection approaches have been tested and evaluated on data from various test sites.

Emneord: Brittle clay, Detection

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REPORT

NIFS, subproject 6 Quick clay

CLIENT

Statens vegvesen (NPRA), Jernbaneverket (NNRA) and NVE (NWRED)

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Detection of brittle materials. Summary report with recommendations.

Final report.

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SUMMARY

The NIFS project is a joint venture between the Norwegian Water Resources and Energy Directorate (Norges Vassdrags- og Energidirektorat NVE), The Norwegian Railroad Administration (Jernbaneverket NNRA) and the Norwegian Public Roads Administration (Statens vegvesen NPRA). In addition to other topics, Task 6 of the NIFS project focus on detection and behaviour of brittle materials.

This work topic concentrates on detection of brittle materials such as quick clay from various field and laboratory methods. The main objective is to evaluate the methods, according to their potential of identifying brittle materials in a rational and reliable way.

The project has been undertaken in the period 2012-2015 in a study titled *"Detection of sensitive materials"*. This report concludes the study, presenting recommended methods and procedures for detection. The report is based on previous reports in the project, where different related criteria for detection of brittle materials have been evaluated. Reference is hence made to NIFS reports and other relevant literature in the literature list.

Recommended procedures include conventional geotechnical soundings, CPTU, electric field vane tests and sampling with laboratory testing. In addition, resistivity measurements carried out downhole (Cone penetration test with resistivity measurements R-CPTU), on the surface (Electrical Resistivity Tomography ERT) or from the air (Airborne Electromagnetic Measurements AEM) are presented. Recommended strategies for integrated use of geotechnical and geophysical site investigations have also been suggested.

The recommended detection principles are partly revised versions of previously well-known principles and classification methods. However, the project also defines new approaches that can be used for more reliable detection. Both previous and new methods should be used with engineering judgement and a critical approach, since the interpretation and classification methods may be misleading in some cases.

In the first phase of the study, the work tasks have been carried out by Multiconsult and SINTEF. In the summary phase, the project has been carried out in close cooperation between Multiconsult/SINTEF, NGI and external scientists, supported by representatives from the NIFS-partners.

LIST OF CONTRIBUTORS

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1 Introduction

1.1 Background

The NIFS project is a joint venture between the Norwegian Water Resources and Energy Directorate (Norges Vassdrags- og Energidirektorat NWRED), The Norwegian Railroad Administration (Jernbaneverket NNRA) and the Norwegian Public Roads Administration (Statens vegvesen NPRA). The main goal with the project is to *“coordinate guidelines and develop better tools for geotechnical design in quick clay areas”*.

Among other topics, task 6 in this project focus on Quick clay, where a study on *"Detection of brittle materials"* has been carried out between 2012 and 2015. This report concludes this study, with recommendations of methods and procedures for detection of brittle materials from various field and laboratory tests. The summary report is based on previous work in this study, where various new and existing detection approaches have been tested and evaluated on data from various test sites. Reference is made to these reports as shown in the reference list.

In the first part of this study, work was performed by Multiconsult and SINTEF in a joint venture. In the summary phase, the project work has been carried out in working group meetings, with members from Multiconsult, NGI, external experts and the NIFS partners.

1.2 Task description

Indication of quick and sensitive clays is an important issue in many projects, since this will change the project assumptions and provide stricter guidelines for the ground investigations. It will also influence geotechnical planning and design, as well as control and documentation routines for the geotechnical work carried out.

The field methods used in Norway today may in many cases give sufficient indications of brittle materials. It is however common practice to carry out soil sampling and subsequent laboratory investigations to verify the presence of such materials. However, in several cases the sounding profiles obtained by conventional methods give misleading indications of quick and sensitive clays. This can either be conservative, indicating quick clay in the field but where the laboratory testing show non-sensitive behavior. More problematic is the non-conservative approach, where sounding profiles show no signs of quick clay, but where such materials are encountered later in the project. Hence, a review of the existing practice for detection of brittle materials is required, where the possibilities and limitations of relevant geotechnical and geophysical field methods are outlined.

The work tasks in this project can be summarised as follows:

- Evaluation of conventional sounding methods and their potential of detecting brittle materials (rotary weight sounding DT, rotary pressure sounding DRT, total sounding TOT)
- Improving CPTU-based classification charts for identification of brittle materials
- Evaluation of resistivity measurements for mapping of quick clay areas (downhole mode (R-CPTU), surface mode (ERT) and airborne mode (AEM))
- Recommended strategy and interpretation methodology based on a combination of geotechnical borings and resistivity measurements for evaluation of presence and extension of quick and sensitive clays

The study has shown that interpretation of results from conventional sounding methods may lead to erroneous information of the ground conditions, where the presence of brittle materials may be both overestimated and underestimated. The report also point at possible explanations for these features.

In Norway, the Cone Penetration Test with pore pressure measurements (CPTU) is one of the most frequently used methods nowadays. With parallel measurement of pore pressure, cone resistance and sleeve friction, a data set is obtained that is well prepared for soil classification. A series of such classification charts have been presented in the literature, but they appear in many cases to be misleading for indication of Norwegian quick and sensitive clays. One aim of this study has hence been to develop improved classification charts for more reliable interpretation of Norwegian quick and sensitive clays.

The great efforts undertaken on mapping of quick clay zones has led to an increasing demand of quicker and more reliable identification of such materials. Today, there is an increasing tendency of using combined geophysical and geotechnical investigations for mapping of quick and sensitive clays. Resistivity measurements, in particular, seem to have a great potential for detection of leached materials, both with respect to quality in the assessments and the extension of the deposit. Resistivity measurements can hence be very efficient in the early stages of a ground investigation, since they provide continuous information of the ground conditions along the established profiles. Geotechnical borings provide constrained information for the individual locations, and information between the boreholes are usually assessed by interpolation or extrapolation. By combining the two approaches, one may obtain a continuous image of the ground conditions, where the information from local boreholes may be used to support and verify the geophysical results.

So far, the most frequently used resistivity method for detection of brittle materials has been 2D-resistivity measurements on the surface (Electrical Resistivity Tomography ERT). The resistivity can however also be measured locally in a borehole by a CPTU with resistivity measurements (R-CPTU). With this equipment it is possible to measure the resistivity of the soil by a separate resistivity module, that is coupled with an ordinary CPTU probe. In addition to the resistivity, the full array of CPTU parameters such as cone resistance, pore pressure and sleeve friction can be used to determine the soil stratification precisely. Airborne electromagnetic measurements (AEM) have been introduced for mapping of quick clay in recent years, and appear to be a very efficient method for this purpose, for example in mapping of large areas or investigations for road or railway projects.

In general, one may say that geophysical methods cover large areas in relatively short time, but with poorer resolution and less refinement than geotechnical tests. By combining geophysical and geotechnical methods, the outcome may hence be a more rational and cost-effective ground investigation.

1.3 Scope of the report

The methods for mapping of brittle materials must be chosen in a cost-benefit perspective, the applicability of the method for the actual ground conditions and the need for data in the project. The summary report in this study contain procedures for detection of brittle materials for commonly used field- and laboratory methods in Norway.

In the summary phase of this study, it has been important to conclude and give recommendations, based on the experiences and observations made with the various detection methods. In particular, this is valid for the resistivity methods R-CPTU, ERT and AEM, where limited experiences exist from practical use. Moreover, it is important to summarize experiences made with interpretation of brittle materials from CPTU and compare these to results from resistivity measurements.

The recording of total penetration force in a CPTU/R-CPTU may be used to deduct the mobilized rod friction. This is an interesting procedure, which so far has produced promising results, both in Norway and Sweden.

Important work tasks in the summary phase have been:

- Summary of experiences and procedures for detection of brittle materials from conventional sounding methods
- Summary of measured resistivity values for brittle materials, with comparison of data from R-CPTU, ERT and AEM
- Develop new identification charts for quick and sensitive clays, based on CPTU/R-CPTU measurements, where derived parameters from cone resistance, pore pressure, sleeve friction and possibly resistivity are combined
- Compare results from electrical vane tests with results from laboratory tests and CPTU
- Evaluate correlations between resistivity measurements with results from laboratory index tests and salt content
- Develop recommended ground investigation strategies for deposits of quick and sensitive clays
- Summary, conclusions and recommendations for selected test methods

1.4 Organization of the study

The basic part of this study was carried out by Multiconsult and SINTEF between 2012 and 2015. This included the following activities:

- Evaluation of conventional sounding methods for detection of brittle materials. NIFS-report no. R46-2012 (MC 415559-RIG-RAP-001), together with a master thesis by Tesfaye Tilahun, NTNU
- Use of resistivity measurements for detection of brittle materials. NIFS-report no. R47-2014 (MC 415559-RIG-RAP-002), together with a master thesis by Alberto Montafia, NTNU
- Field study with resistivity and electric field vane tests (R-CPTU, ERT, EFVT) at selected test sites. NIFS-report no. R101-2015 (MC 415559-RIG-RAP-003))

Reference is made to these reports for further descriptions (in Norwegian).

In the summary phase, a working group for the making of a summary report with recommendations for practical use was established. This group included representatives from Multiconsult, SINTEF, NGI, University College Dublin and the NIFS-partners. The following persons contributed:

- **Multiconsult:** Rolf Sandven, Alberto Montafia and Anders Samstad Gylland (from august 2015)
- **SINTEF:** Anders Samstad Gylland (to august 2015)
- **NGI:** Kristoffer Kåsin and Andi A. Pfaffhuber (with contributions from Sara Bazin and Helgard Anschütz)
- **University College Dublin (UCD)**: Mike Long
- **NIFS-partners:** Ingrid Havnen (NWRED), Hanne Bratlie Ottesen (NPRA) and Mostafa Abokhalil (NRRA)

The Norwegian Geotechnical Society (NGF) has also supported the project economically. A short version of the summary report will hence be made, becoming a new issue in the series of NGF Guidelines (NGF Guideline 12).

1.5 Definitions and terminology

In this report, quick clay, sensitive clay and brittle materials have been defined according to NGF Guideline 2 *Symbols and terminology in geotechnics* and NVE's *Guideline for planning and development of quick clay areas* (NVE report 7/2014).

Quick clay: Clay which in the remoulded state has a shear strength c_r less than 0,5 kPa.

Sensitive clay: Clay showing a certain level of strength loss in the remoulded state. In general, a clay has low sensitivity if $S_t < 8$, medium sensitivity for $8 < S_t < 30$ and very high sensitivity if $S_t > 30$ (S_t = ratio between undisturbed and remoulded shear strength).

Brittle behaviour: Brittle materials are clays and silts that exhibit a considerable loss of undrained shear strength for increased strains beyond the peak strength (ref. Figure 1.1). NVE's Guideline classifies all materials with a remoulded shear strength c_r less than 2,0 kPa and sensitivity $S_t > 15$ as brittle materials. Both criteria have to be satisfied.

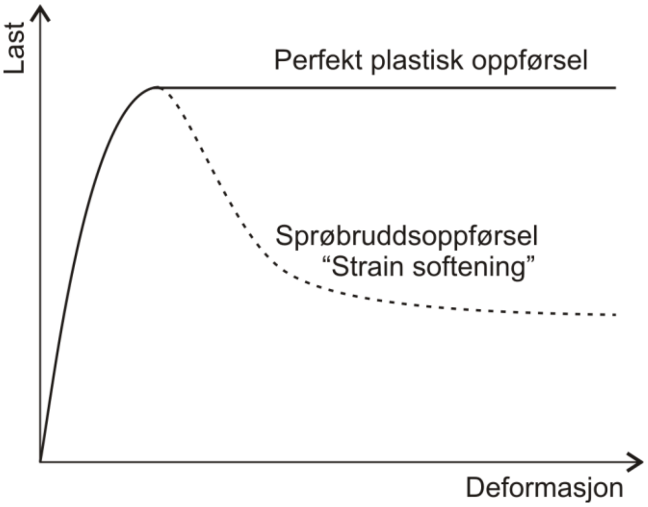


Figure 1.1 Perfect plastic and brittle behaviour in geological materials.

Clays that are not considered as brittle materials may also show a considerable degree of strain softening. It is worth mentioning that NIFS report 88/2014 does not show any correlation between sensitivity and degree of brittleness in triaxial tests on Norwegian clays. This indicates that the present definition of brittle materials is not the final one, and that a new definition may be developed when a better understanding of this feature is obtained.

1.6 Test sites used in the study

The collection of test sites in this study has been established to evaluate various methods for detection of brittle materials. To obtain a sufficiently large amount of sites, cooperation with the other NIFS partners was established, such as NGI, NPRA, NTNU/SINTEF and NGU, with Rambøll as an external partner. In the NIFS-project, two new test sites were established (Klett and Fallan), which are documented in NIFS report R101-2015 (Multiconsult 415559-RIG-RAP-003). In addition, several other test sites have been included. These sites are also well established, either by research studies or in commercial projects. In the selection of test sites, a regional distribution with sites in Central Norway (Trøndelag) and Eastern Norway was emphasized. In addition, variations in preconsolidation stress and clay content was necessary.

Table 1.1 Overview of selected test sites with available geotechnical information.

Test site	Sounding	CPTU	R-CPTU	ERT	Vane	Sampling	Selected references
EASTERN NORWAY							
E16 Kløfta, section Nybakk – Slomarka	TOT	x	x	x AEM	-	72/Block	Christensen, C.W. et al (2015) Anschütz, H. et al (2015) NGI report 20120491-01-R(2013)
Smørgrav/ Vestfossen	DRT	x	x	x	-	72	NGI report 20081135-1 (2009) NGI report 20100136-1-R (2010) Donohue et al (2009) Donohue et al (2012) Pfaffhuber et al (2010) Bazin et al (2013)
CENTRAL NORWAY							
Tiller	DRT/TOT	x	x	x	x	54/76/Block	NTNU PhD and MSc theses: Sandven (1990), Ørbech (1999), Seierstad (2000), Long (2005), Yesuf (2008), Gylland (2011/2012), Gylland (2013), Sandene (2010), Holsdal (2012)
Esp, Byneset	DRT/TOT	x	x	x	-	54/76/Block	Thakur (2012) NTNU MSc theses: Hundal (2014), Torpe (2014), NGI files
Klett south	DRT/TOT	x	x	x	x	54/76/Block	Multiconsult 415531-RIG-RAP-003 (2014). NIFS R101-2015.
Klett north	DRT/TOT	x	x	x	-	54/76/Block	NGF sampling seminar 2014
Dragvoll	DRT	x	x	x	-	54/Block	NTNU MSc thesis: Montafia (2013)
Fallan	DRT/TOT	x	x	x	x	54	Multiconsult r414622-1 (2011) Multiconsult n414622-1 (2011) NIFS R101-2015
Rein, Rissa	DRT/TOT	x	x	x	-	54/76/Block	NTNU MSc thesis: Kåsin (2011) Multiconsult r414792-2 (2012)
Nidarvoll	TOT	x	x	x	-	54	NTNU MSc thesis: Hundal (2014)
Rødde	DRT/TOT	x	x	x	-	54	NGI report 20091127-00-73-R Multiconsult r413809-1
Ranheim west	TOT	x	x	x	-	54	Multiconsult 416235-RIG-RAP-002 (2014)
Hommelvik seaside	TOT	x	x	x	-	54/72	NGI report 20130532 (2013) NGI report 20140383 (2014)

Table 1.1 provides a detailed overview of the investigations carried out at the selected test sites.

The following investigations have been included in the study:

Soundings

- Rotary weight sounding (DT)
- Rotary pressure sounding (DRT)
- Total sounding (TOT)
- Cone penetration tests with pore pressure measurement (CPTU)
- Cone penetration tests with resistivity measurement (R-CPTU)

Soil sampling

- Piston sampling (ϕ54 mm, ϕ72-76 mm) (PS)
- Block sampling (ϕ250 mm Sherbrooke, ϕ160 mm NTNU) (BS)

In situ tests

- Electrical field vane test (EFVT)

Special tests

- Surface resistivity measurements (Electrical Resistivity Tomography) (ERT)
- Airborne Electromagnetic Measurements (AEM)

A detailed overview of performed investigations and properties of the selected test sites is summarized in Enclosure A, whereas a short description of geotechnical and geophysical data for the sites, along with the most relevant soil profiles are shown in Enclosure B.

2 Relevant methods for detection of brittle materials

In present day site investigations, relatively few methods are utilized for detection of brittle materials, at least in ordinary design and mapping projects. It is however possible to use all sounding methods based on a constant penetration rate, and where the penetration force measured on top of the penetration rods or another measure of the penetration resistance is recorded. The following sounding methods are considered the most interesting:

- Rotary weight sounding (primarily due to the large amount of historical data)
- Rotary pressure sounding
- Total sounding (rotary pressure sounding in combination with rock control drilling)
- Cone penetration test with pore pressure measurement (CPTU)

Rotary weight sounding (DT) was previously the most popular method for this purpose, but the method is now substituted by other, drillrig-based methods such as rotary pressure sounding (DRT) and total sounding (TOT). The method is however still relevant due to the large amount of historical data

Conventional sounding methods such as rotary pressure and total sounding may in many cases be sufficient for detection of brittle materials. However, this study has shown that these methods may give misleading interpretation in such materials, both in a conservative and non-conservative way. This implies that brittle materials cannot always be detected by these methods alone.

Over the last 15-20 years, the use of CPTU in land-based projects has escalated, and the method is today a household method in Norwegian practice, both as a sounding and in situ test method. The results provide in most cases a very detailed and precise determination of soil stratification and type. The results are also used for direct or indirect interpretation of geotechnical parameters. The method has also a certain potential for detection of brittle materials, but shortcomings exist in the use of presently available soil identification charts. Swedish studies have shown that the detection can be improved by adding measurement of resistivity (R-CPTU) and total penetration force to the classical recordings (Løfroth et al, 2010).

Vane testing is also a valuable method since it is the only in method that can determine the remoulded shear strength and sensitivity by direct measurements and not through empirical relationships. The method can, by using the appropriate equipment, again become an important method in Norwegian geotechnical practice.

2D resistivity measurements on the surface (Electric Resistivity Tomography ERT) have been used for several years for applications in geological and geotechnical mapping. ERT gives a continuous resistivity profile that can be several hundred meters long, and may also reach deep soil layers and the bedrock.

The method has now become very useful for mapping of deposits with quick and sensitive clay (Solberg et al, 2008; Rømoen et al, 2010). In recent years, airborne methods (Airborne Electromagnetic Measurements AEM) have also been used for mapping of soils and rock, and it is now possible to detect deposits of leached clays by this method with some accuracy (Pfaffhuber et al, 2010). In addition, downhole measurements of resistivity by R-CPTU can supplement the surface-based and airborne mapping methods, where the R-CPTU data may be used in processing and interpretation of the ERT- and AEM-data by constrained inversion.

ERT and AEM provide continuous information of the ground conditions in an area, whereas geotechnical soundings and in situ methods give soil data only in scattered locations. Pockets of quick clay with limited extension may hence not be discovered in a conventional geotechnical site investigation. Resistivity measurements can be used in an early stage of the site investigation to detect the extension of possible hazard zones with leached clay. This can be supplemented by strategically placed borings for more precise determination of the soil conditions. In this way, a more rational site investigation may be obtained, with a larger potential of detecting zones with quick or sensitive clays.

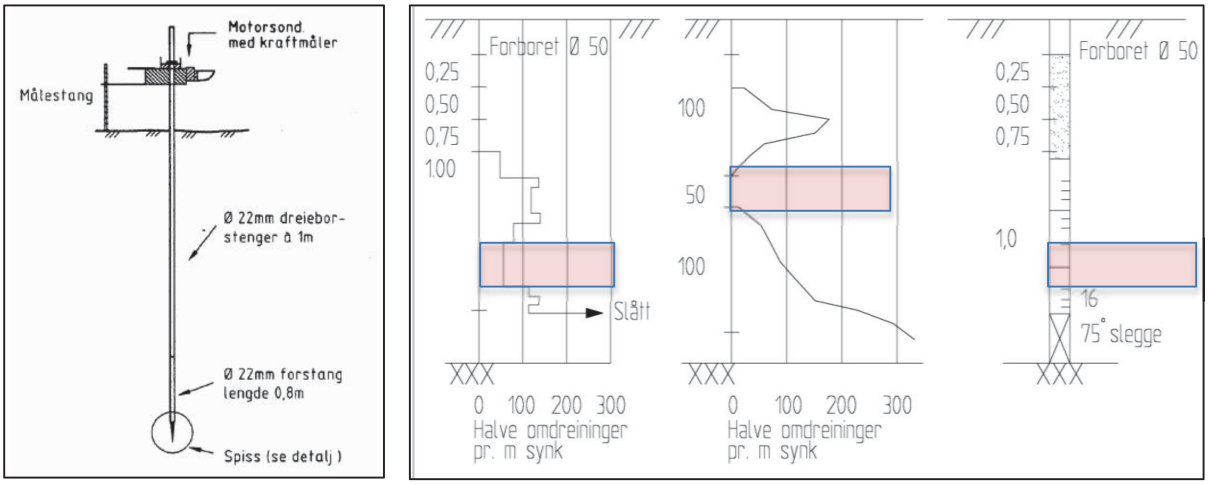
Independent of method and strategy, the results from field investigations have to be calibrated and compared to the results from laboratory investigations. The verification of quick clay is commonly obtained from the remoulded shear strength c_r in a fall cone test. However, by having reasonably reliable field methods, one may reduce the amount of expensive and time-consuming sampling and laboratory testing.

In this report, a review of the most relevant methods for quick clay detection is presented, including a discussion of possibilities and limitations of each method.

2.1 Conventional sounding methods

2.1.1 Rotary weight sounding

Rotary weight sounding is a simple sounding method that can provide an impression of the relative strength of the ground. The method may also indicate the depth to a firm layer.



a) b) c)

Figure 2.1 Equipment for rotary weight sounding.
a) Equipment and test principles for rotary weight sounding
b) Presentation of test results according to NGF
c) Presentation of test results according to the National Public Roads Administration NPRA
Red marking: Possible quick clay layer

The results may to a certain degree be used for evaluation of the ground conditions, for example presence of gravelly, sandy or clayey materials. The method is however mainly used in soft to medium soils with a limited amount of coarser fragments and materials. It is also convenient to use at sites where access with heavy drillrigs is difficult or impossible.

By rotation of the drill-string, the number of half-turns of the rod system are recorded per 20 cm penetration with 100 kg (1 kN) normative weight on the rods. Both machine-based and manual penetration of the drillstring is possible, see Figure 2.1 a. The number of half-turns per depth unit can be different by machine and manual operations.

The results from a rotary weight sounding can be presented by plotting the number of half-turns of the rod system per m penetration along the horizontal axis, see Figure 2.1 b. If predrilling of the borehole is used, this is marked on the drawing. The load in kN is given on the left side of the borehole column, see Figure 2.1 b. The results can also be shown in a diagram with use of bars, according to the procedures used by NPRA (Statens vegvesen), see Figure 2.1 c. A full bar corresponds to 100 half-turns, whereas a half bar is used for every 25 half-turns. In this presentation, the bars will hence be drawn with large internal distance when penetrating soft or sensitive layers. Penetration without rotation is marked by shading or another clearly visible pattern. Penetration with applied blows on the drill-string is marked by a cross and the number of blows, and the utilized ramming equipment is usually reported. Figure 2.1 (b) shows results from sounding through a quick clay layer, where the drilling assembly has sunk for 50 kg load without rotation.

Rotary weight sounding was previously a frequently used method, and data from old ground investigations often include results from this method. The need for drillrig-based sounding and larger sounding depths has increased in later years, and most of the previous rotary weight sounding has now been substituted by more robust sounding methods with higher penetration capacity. However, even if the use is limited today, the method can be a good supplement in steep terrain, and where the required sounding depth is limited (10-15 m).

Reference is made to NGF Guideline 3 and NS-EN ISO/TS 22476-10 for a more detailed description of test equipment and procedures.

2.1.2 Rotary pressure sounding

The rotary pressure sounding is a method where the drill-string is pushed and rotated into the ground with constant penetration and rotation rate. The sounding resistance corresponds to the penetration force required to obtain the normative penetration conditions.

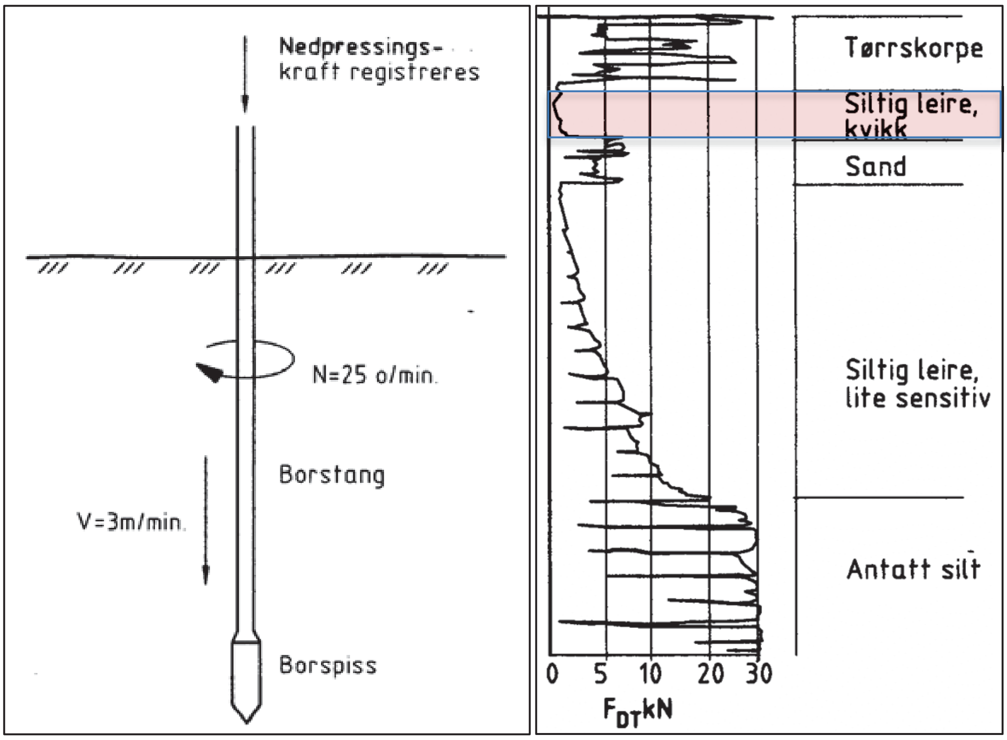
Rotary pressure sounding can be used in most types of soils, from clays to gravels. The results can be interpreted for indication of soil stratification and the depth to firm layers or bedrock. The method usually shows good ability to penetrate even denser soils, but will usually terminate against large stones or boulders. Rotary pressure sounding can hence not penetrate the bedrock surface, but may indicate its location.

The principles of rotary pressure sounding are shown in Figure 2.2. During penetration, the procedure shall satisfy the following conditions:

- Penetration rate: 3 ± 0,5 m per min.
- Rotation rate: 25 ± 5 rotations per min.

It is necessary to use hydraulic drillrigs to advance the drillstring. The drillrig should have a minimum torque capacity of 1,0 kNm, and should suffice a thrust of 30 kN during penetration. An example of a sounding diagram in layered soil with a thin layer of quick clay is shown in Figure 2.2.

If the penetration resistance exceeds 30 kN, the sounding continues with increased rotation rate. One may also use so-called “pumping”, where the drillstring is lifted and pushed in cycles while the rotation rate is increased to enable further penetration. If this procedure is applied, interpretation of the curve becomes difficult and may not give a valid indication of soil type.



a) *b)*

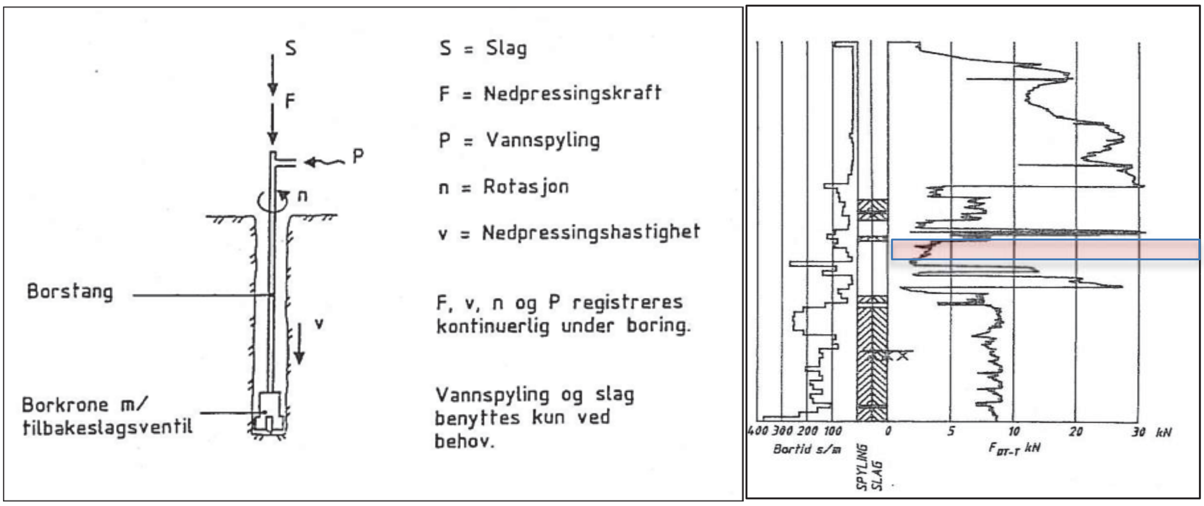
Figure 2.2. Rotary pressure sounding (according to NGF Guideline 7)
a) Equipment and test principles for rotary pressure sounding
b) Sounding result in stratified deposit with possible thin quick clay layer
Red marking: Possible quick clay layer

Reference is made to NGF Guideline 7 for a detailed description of equipment and test procedures.

When the drillbit advances into the ground, the sounding resistance will depend on the materials encountered. The resistance curve may hence be used for an experience-based interpretation of soil type. The soil type and ground conditions can then be evaluated, unless the content of stones and boulders is too large and the soil layers are too dense to be penetrated. For example, layers of silt and sand incorporated in a clay matrix can be identified by a sudden increase in the penetration force. Similarly, a clear boundary between the dry crust and natural clay will appear when sounding in a clay deposit.

2.1.3 Total sounding

Total sounding is used to determine soil stratification and depth to dense strata and the rock surface. The method also enables drilling through gravelly material and moraines and into the bedrock. The method can hence be used for verification of the bedrock surface by drilling minimum 3 meters into it. To be able to carry out total sounding, a hydraulic drillrig with a percussion hammer and equipment for flushing must be used. Use of water as flushing medium is recommended. Air flushing can be used in some cases when water supply is restricted, but shall never be used for drilling in quick clays. When using air flushing, air bubbles can disturb large volumes of quick clay due to volume expansion during pressure reduction. This can trigger slides in areas with critically low stability, and may also cause large settlements.



a) *b)*

Figure 2.3. Total sounding (according to NGF Guideline 9).

a) Equipment and test principles for total sounding

b) Sounding result in stratified deposit with possible thin layer with quick clay.
Red marking: Possible quick clay layer

Total sounding combines the sounding principles from rotary pressure sounding and rock control drilling. In rotary pressure mode, the drilling rods are penetrated into the ground with constant penetration and rotation rate, see Chapter 2.2 and Figure 2.3. If this procedure does not give sufficient penetration, the operation is switched to rock control mode. The sounding then proceeds by first increasing the rotation rate, then flushing is applied and finally ramming with flushing and rotation. The normal sounding procedure (rotary pressure mode) shall be used as soon as the dense stratum is penetrated. Reference is made to NGF Guideline 9 for a detailed description of equipment and test procedures.

The penetration force is recorded with an electronic load cell or similar. Use of increased rotation, hammer blows and flushing are recorded during drilling.

The sounding results are presented in a diagram with a continuous curve for penetration force where the sounding has been performed in rotary pressure mode, see Figure 2.3. Use of increased rotation is marked with a cross on the diagram. Use of hammer blows and flushing is marked by shaded or hatched columns in the diagram. The results can be used to evaluate soil type and the relative stiffness of the materials.

During drilling in rock, the penetration is recorded as number of seconds per meter drilling. The penetration may indicate the rock quality and in some cases the thickness of a weak zone, cracks or other inhomogenities.

2.2 Cone penetration test with pore pressure measurements (CPTU)

The cone penetration test with pore pressure measurement (CPTU) is performed with an instrumented cylindrical probe with a conical tip that is penetrated into the ground at a constant penetration rate of 20 mm/sec (1,2 m per minute). The probe contains electronic transducers for recording of load against the conical tip, friction force against the friction sleeve and the pore pressure at one or more locations along the probe surface. The sleeve friction is measured on a 15-30 cm long instrumented friction sleeve located behind the conical tip. A location immediately above the conical tip is selected as reference level for pore pressure measurements (u_2). A slope indicator (inclinometer) picks up the slope of the rod system referred to the vertical axis.

The measured pore pressure corresponds to the water pressure developed during penetration of the probe into the ground. It is hence very important that the measuring system reflects the true variation of the penetration pore pressures. All components of the hydraulic system including the porous filter or open slot, transfer channels and pressure chamber, shall hence be saturated by a liquid or other media before the penetration starts. Sufficient measures shall be undertaken to maintain the saturation throughout the test.

The results from a CPTU-sounding can be used to determine:

- Stratification
- Soil type
- In situ layering
- Mechanical properties
  - Shear strength
  - Deformation- and consolidation properties

CPTU-results can be used for interpretation of mechanical parameters. This may reduce the need of expensive soil sampling and laboratory tests and result in a rational and cost-effective soil investigation.

CPTU is well suited for tests in clays, silt and sand, but are less suited in coarser soils like gravels and soils with a large content of stones or cobbles. In such cases, the equipment may easily be damaged.

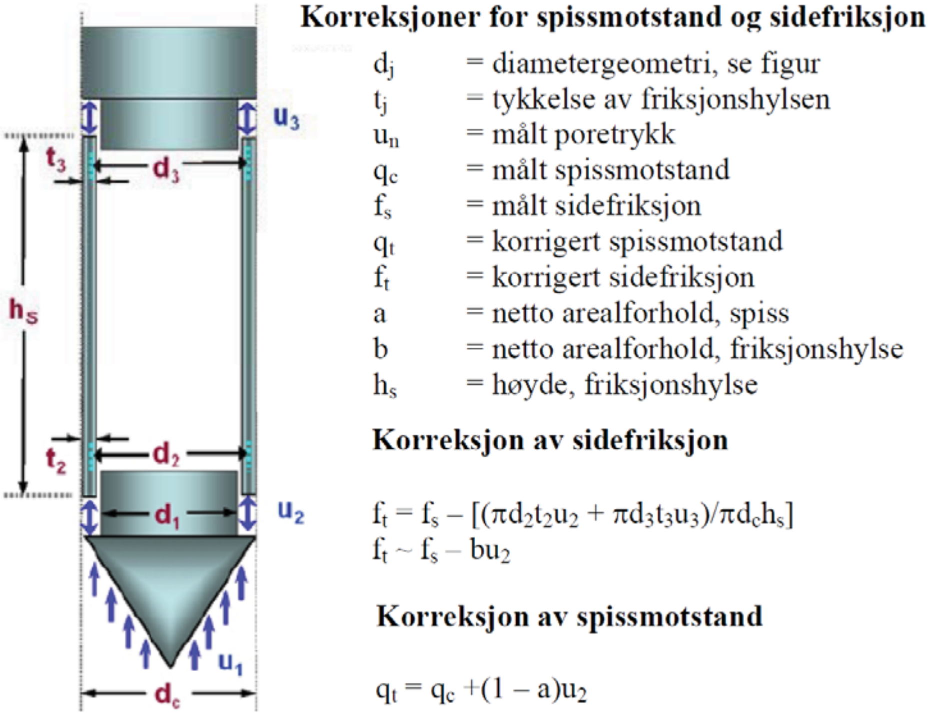
CPTU is a more complicated method than the conventional rotary pressure and total sounding methods, and the performance of the method requires thorough preparations and accuracy in testing. On the other hand, the method provides detailed information of soil stratification and encountered soil types, and the mechanical properties of the penetrated soils can also be interpreted.

The total penetration force can easily be measured in a CPTU. This information may be used to deduce the mobilized friction along the rods in addition to the sleeve friction, which in turn may indicate layers with quick or sensitive clay. This procedure is described in further details in Chapter 3.2.3 in this report.

Due to the design of the probe with different diameters of the internal end surfaces $d_{j\ j\ =\ 1\text{-}3}$, an unbalanced force will result from the pore pressure acting in the joint between the conical part and the friction sleeve. Both the measured cone resistance q_c and the sleeve fiction f_s are influenced by this effect and have to be corrected. The net area ratios for the probe, **a** (for cone resistance) and **b** (for sleeve friction) are used for this correction and have to be known for the specific probe.

Figure 2.4 shows how these corrections are carried out for the measured cone resistance and sleeve friction, respectively. The sleeve friction is difficult to correct adequately since the pore pressure behind the sleeve (u_3) is unknown. It is hence acceptable to use the uncorrected (measured) sleeve friction f_s in all relations. This correction is significant for tests in clays and silts, where large pore pressures are developed during sounding.

The performance quality of CPTU is classified in four Application classes (1-4), depending on the prevailing ground conditions and the required accuracy of the measurements. Application class 1 (best class) is used for soft to very soft, homogenous soil conditions and are always required for design evaluations in quick clay areas (NVE, 7/2014).



Korreksjoner for spissmotstand og sidefriksjon

d_j	= diametergeometri, se figur
t_j	= tykkelse av friksjonshylsen
u_n	= målt poretrykk
q_c	= målt spissmotstand
f_s	= målt sidefriksjon
q_t	= korrigert spissmotstand
f_t	= korrigert sidefriksjon
a	= netto arealforhold, spiss
b	= netto arealforhold, friksjonshylse
h_s	= høyde, friksjonshylse

Korreksjon av sidefriksjon

$$f_t = f_s - [(\pi d_2 t_2 u_2 + \pi d_3 t_3 u_3)/\pi d_c h_s]$$

$$f_t \sim f_s - bu_2$$

Korreksjon av spissmotstand

$$q_t = q_c + (1 - a)u_2$$

Figure 2.4 Equipment and correction procedure for CPTU measurements (according to NGF Guideline 5).

In a CPTU, the test results shall be presented as continuous profiles versus the penetration depth:

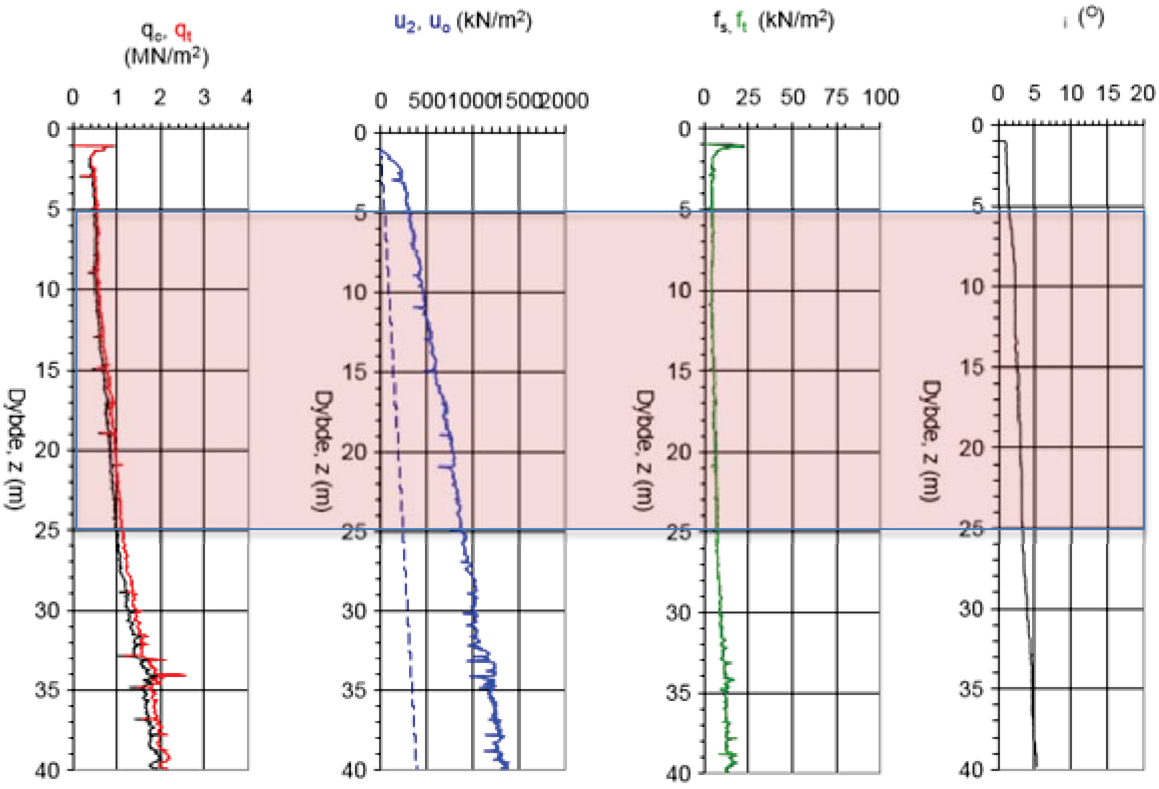
Corrected cone resistance – depth	q_t (MPa) - z (m)
Sleeve friction – depth	f_s (kPa) - z (m)
Total pore pressure, reference level – depth	u_2 (kPa) - z (m)
Measured rod inclination	i (°) – z (m)

An example of CPTU records in a quick clay is shown in Figure 2.5 (Klett test site, Multiconsult 415559-RIG-RAP003). In the figure, the quick clay layer is shown with red shading, and it is remarkable that neither the cone resistance (red line), the pore pressure (blue line) nor the sleeve friction (green line) indicate the transition between quick and non-sensitive clay. On this background, one may claim that it is usually not possible to detect quick or sensitive clays from the measured CPTU data alone. The results have to be presented as derived parameters, preferably using dimensionless, normalized values.

Several factors in choice of equipment, planning and performance of CPTU may influence the accuracy in measurements, such as:

- Measuring range and resolution of the transducers
- Calibration accuracy
- Temperature influence on the probe with electronic transducers
- Zero shift for electronic transducers
- Saturation of the pore pressure system
- Rod inclination
- Wear of the probe (conical tip and friction sleeve)

The zero shift (difference in zero values before and after penetration) for cone resistance, sleeve friction and pore pressure shall, together with other contributions to the inaccuracy, be documented and evaluated according to the required accuracy in the relevant Application class.



a) b) c)

Figure 2.5 CPTU-profile in quick clay (ref. Klett test site, MC 415559-RIG-RAP003)

a) Corrected cone resistance, q_t

b) Pore pressure, u_2

c) Sleeve friction, f_s

Red marking: Verified quick clay layer from laboratory tests

For detailed information about test equipment and procedures, reference is made to NGF Guideline 5 and NS-EN ISO 22475-1. These documents also present the requirements for the four Application classes.

2.3 Resistivity measurements

The electric resistivity of soils and rocks is generally a function of porosity, the ion content of the pore water, salinity, clay content and presence of charged minerals such as graphite and some sulfides. In deposits of brittle materials, the salt content is significantly less than in intact, marine clays due to leaching of salt from the pore water. The resistivity will hence normally be higher in brittle materials than in the intact marine clays.

For clays in general and for leached clays in particular, it is mainly the salt content that influences the resistivity of the clay, at least for salt contents higher than ca. 1 g/l (Montafia, 2013). By measuring the resistivity of the soils, one may hence be able to deduce the potentially leached zones according to the classification table in Figure 2.6.

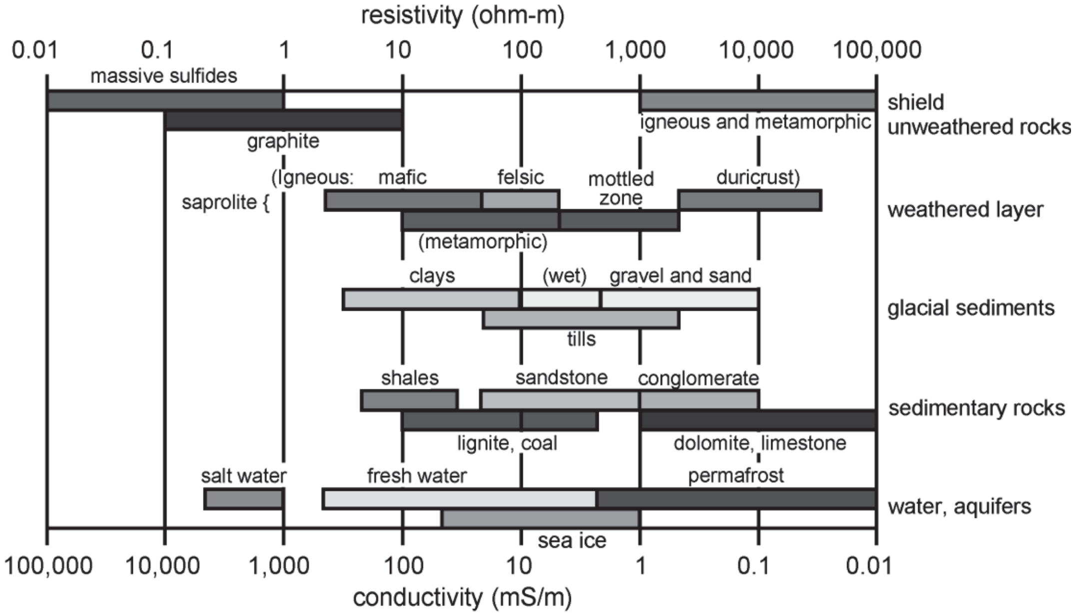


Figure 2.6: Typical resistivity for different soil and rock types (Pakacky, 1987).

The electric resistivity of the soil can be measured in the laboratory, by downhole measurements in the ground (R-CPTU), from the terrain surface (ERT) or by airborne measurements (AEM). Some of the most relevant methods are described in the next chapters.

2.3.1 Downhole measurements with resistivity probe (R-CPTU)

Resistivity measurements can be a useful tool in mapping of brittle materials. This is particularly important when comparing the measured resistivity to the traditional data in a cone penetration test with resistivity measurement (R-CPTU).

The sounding equipment used for R-CPTU consists of an ordinary CPTU probe and a resistivity module mounted behind the probe, see Figure 2.7. To enable direct measurements of the resistivity, the electrodes need to be in contact with the soil volume where the measurements shall take place. The module is powered by batteries, and it can read, store and transmit measured data acoustically through the rods or via an electric cable to a receiver on the surface. The measured data can also be stored on a digital memory-card mounted in the probe.

Scandinavian manufacturers of R-CPTU equipment have chosen to equip their resistivity probes with four ring-electrodes. The two outer electrodes transmit electric current into the soil, whereas the two inner electrodes measures the difference in potential. The distance between the electrodes defines the configuration. Both Geotech and ENVI use a configuration with equal internal distances, also known as the Wenner-α configuration. Other manufacturers produce resistivity modules with two electrodes, such as the manufacture from Gouda Geo-Equipment (The Netherlands) in Figure 2.7b.

Application of current in the soil is not similar for all probe types. The Geotech probe sends short impulses of DC current with equal intensity of 200 units per second into the soil. Some probes, however, use AC current where the intensity can be adjusted.

The resistivity module is usually calibrated in brine solutions of salt and water. When the salt concentration is known and the temperature is measured, the electrical conductivity of the solution can be determined. This is used as reference during the measurements.

a) Geotech R-CPTU probe with resistivity module b) Mounted probe with resistivity module, Gouda

Figure 2.7: R-CPTU equipment with four (a) and two electrodes (b).

The additional time for a R-CPTU compared to an ordinary CPTU is only a few minutes. This is the time needed to mount the resistivity module on the battery package.

If the diameter of the resistivity module is larger than the diameter of the CPTU-probe, a transition rod with length of l > 500 mm shall be used. Apart from that, the sounding procedure is similar to an ordinary CPTU. In the Nordic countries, R-CPTU is mainly used for detection of leached clays, whereas in the rest of the world the method is used for tracing of contaminants in the ground.

2.3.2 Electrical resistivity tomography (ERT)

Electrical resistivity tomography (ERT) is a geophysical test method that uses DC current for measurement of the resistivity distribution in the ground. The current is applied on the soil volume by using short steel electrodes installed at the terrain surface, penetrating 10-20 cm into the ground (see Figure 2.8). By measuring the differences in electric potential, a measure of the soil resistance is obtained for all electrode locations.

Most types of ERT- equipment also measures the chargeability of the ground, the so-called induced polarization (IP). This parameter is a complementary physical parameter that is useful in evaluations of contamination, detection of minerals or ground water conditions. By processing the data and running an inversion algorithm, a 2D or 3D resistivity model of the ground is obtained (see Figure 2.9). By integration of the resistivity model with data from borings and the geological knowledge of the area, the resistivity can be interpreted in terms of a geological ground model. This principle rests on the assumption that the resistivity mainly is determined by sediment or rock type.

Performance of the test

An ERT-cable can be placed in an area as long as one can access the area by foot. It is also possible to cross roads, as long as the traffic is regulated conveniently. The measuring profiles are organized in one or more straight lines. Present day equipment can measure potentials on several parallel channels, and the total time of measurements in a profile takes approximately one hour. The National Geological Survey (NGU) has developed a guideline for resistivity measurements in potential quick clay areas (NGU, 2011).

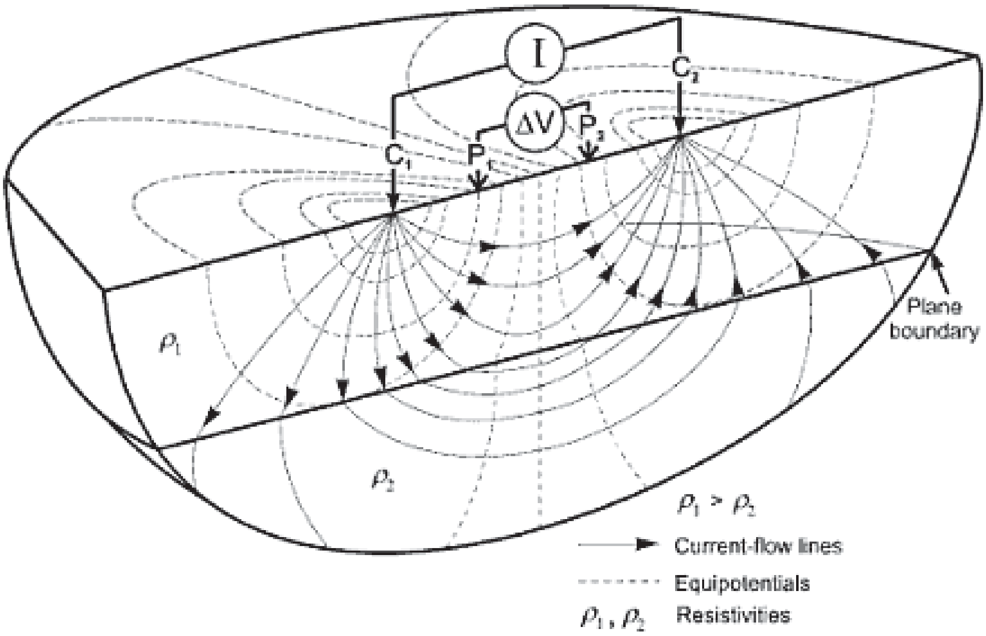


Figure 2.8: Principal sketch of ERT measurements. Electric current is send through the soil by 2 electrodes (C), while the power is measured on several locations (two in the illustration, P) (Knödel et al 2007).

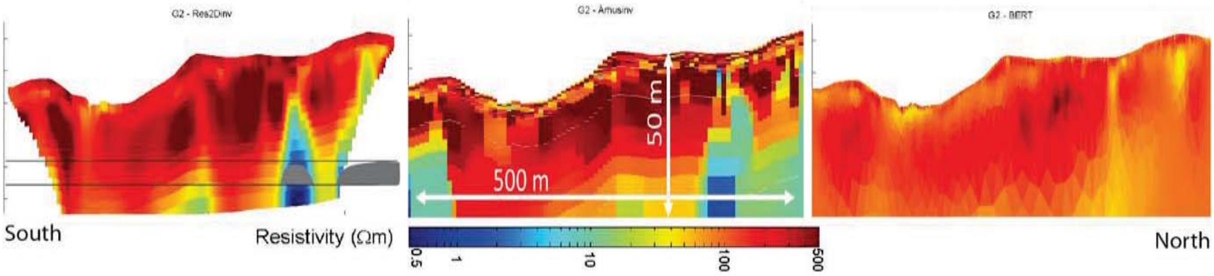


Figure 2.9: ERT models calculated with three different inversion programs, using different inversion algorithms.

<u>Remarks 1:</u> There exists no unique model for the measurements, and use of different calculation models can illustrate the uncertainty. Low resistivity in this example reflects black shale, which was encountered in a tunneling project (marked with grey in the model to the left).

<u>Remarks 2:</u> There exists no standardized colour code for presentation of resistivity measurements. It is recommended to use the same colour code for one specific project.

Previously, several surface configurations were utilized for arranging the ERT-profiles (e.g. dipole-dipole, Wenner). These configurations had advantages and disadvantages with respect to resolution and penetration capacity. With modern multi-channel equipment, the *Gradient array* is the most popular method. Some advantages may be obtained by using the *Dipole-dipole* lay-out, but this is probably not justified due to the extended measuring time for this configuration.

A general estimate of the investigation depth is a reach of about 10-20 % of the profile length, depending on the resistivity distribution in the soil. The resolution obtained depends on the electrode spacing. Near the surface, the resolution in depth and along the profile is about half the electrode spacing, but becomes poorer with depth due to the increase in the influenced soil volume. Good planning of the measuring profile is hence important, but one usually has to compromise between investigation depth and resolution in the measurements. It is however possible to measure a number of adjacent profiles with several different electrode spacing to obtain a combination of high resolution and sufficient penetration depth. High resolution is particularly important if the aim is to separate the small differences in resistivity between salt and leached clay.

Geotechnical applications
ERT-measurements on the surface can be used for the following geotechnical applications:

- **Mapping:** Determination of depth to bedrock and thickness of soil layers. By integration of geotechnical information from for example CPTU, total sounding and rotary pressure sounding with ERT-data, the depth to the bedrock surface can be precisely and continuously mapped. In addition, information of the soil deposit can be obtained, such as quick clay pockets or presence of coarser layers.
- **Detection of brittle materials:** The salt content, and hence the electrical conductivity for brittle materials (quick and sensitive clays), is usually lower than for non-sensitive clays. It may hence be possible to distinguish between salt and leached clays by ERT, assuming that the resolution of the measurements is sufficient.
- **Slide risk/rock quality:** Areas where rock falls are triggered are usually characterized by cracks and tectonically active fault zones in the rock. These zones may include layers of clay, and are also usually water saturated.
- **Archeological objects:** Old structures of timber, stone or bricks may appear as small resistivity anomalies, if they are surrounded by sediments with high conductivity, e.g. salt marine clays.
- **Mapping of environmental risks:** Industrial waste-fills and similar structures may be mapped by ERT. Using induced polarization (IP), chargeable elements such as for example creosote, alcohols and metal ions may be revealed.

Limitations
ERT is a robust method that give good results in most cases. However, some limitations and challenges have to be noticed:

- **Existing infrastructure:** The measurements are sensitive for all objects and media within the zone influenced by the applied current. This implies that electrical cables, tubes and structures influence the resistivity model. However, this does not mean that the method cannot be used with good results, but it can reduce the reliability of separating geological signals from the response from underground installations.
- **Depth resolution versus resistivity resolution:** The resistivity models are processed in a way that tries to interpret the measurements by continuously increasing or increasing resistivity in depth and along the profile. This means that the transition from marine clay with low resistivity to rock with very high resistivity may be misleading, particularly if the thickness of the clay layer is limited. The resistivity of the clay will then appear higher than the real value, which can cause misleading interpretation of the clay.

2.3.3 Airborne electromagnetic measurements (AEM)

AEM (Airborne Electromagnetic measurements) are used to map the electrical resistivity of the ground in a larger area. The method is traditionally used in the mining industry for tracing minerals in the ground, but modern airborne systems may have sufficient resolution to allow use in hydrological and geotechnical applications. The most recent results indicate that it is possible to distinguish salt from leached clays in AEM, similar to what can be done by R-CPTU and ERT-measurements.

Different AEM systems are available, some adapted to the need of large penetration depths for mineral tracing, others for more shallow applications in hydrogeology and geotechnics. These applications require high resolution measurements (NGI report 20130058-02-R_NO). All systems have in common that a magnetic field generated by the antenna induces current in the ground, which distributes downward and outwards as shown in Figure 2.10. The rate of change in the electromagnetic field these currents produce, is recorded by a secondary coil. By inversion of the measured data points, the resistivity distribution in the ground can be modelled (see Figure 2.10).

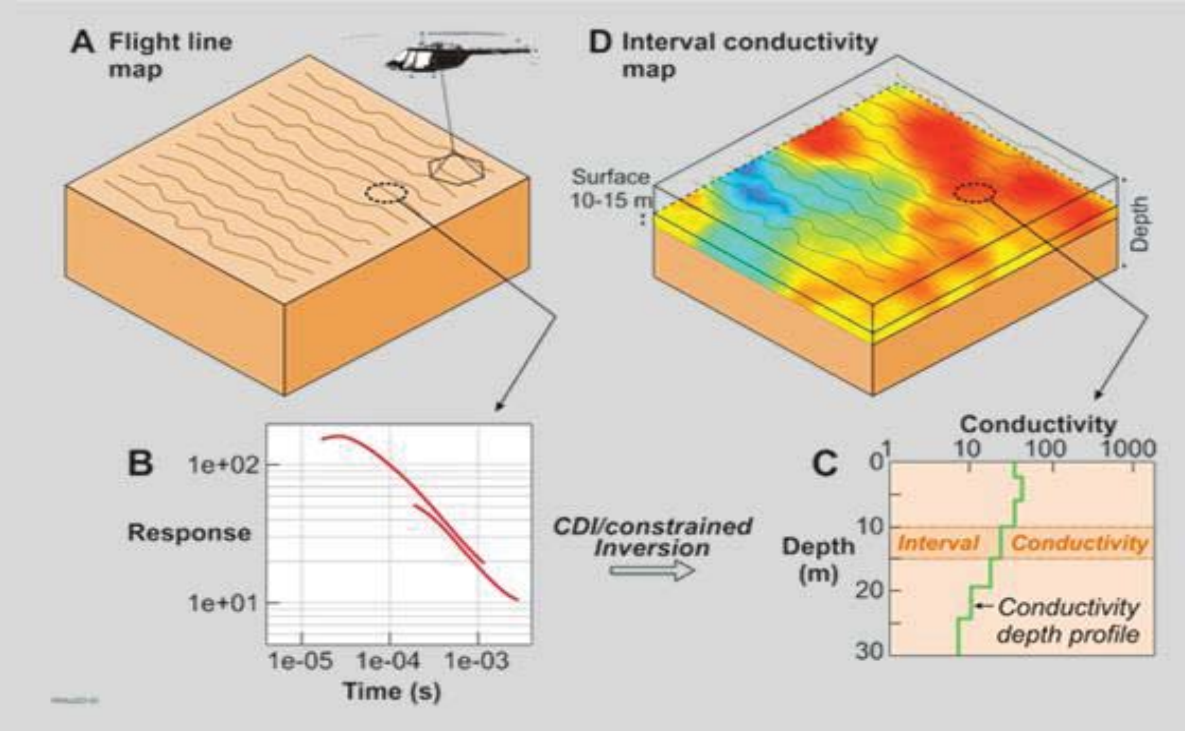


Figure 2.10: Principal sketch of AEM: The measurements are collected along flylines and are inverted to a resistivity model (Source: crcleme.org.au).

The possible investigation depth may vary from 50 m to about 500 m, depending on the geology and type of soil in the area, the AEM system and the influence of noise from surrounding infrastructure. The vertical resolution may be as good as 3-6 m close to the surface, but it gradually gets poorer with depth.

The lateral resolution is determined by the size of the soil volume where current is induced. A typical estimate is that > 90 % of the signal from the ground origins from a perimeter about 3-4 times the flying height of the antenna. This means that one measurement defines a half-sphere with about 100 - 150 meter diameter. The resolution is also influenced by the processing method. Experience shows that structures falling steeper than 30° will not be correctly depicted, but will appear with a more gentle slope compared to the true conditions. However, special processing tools that are more adapted to vertical or sloping structures are available.

Performance of the test

AEM data can be collected both over land and in sea areas, and may distinguish between cultivated land, forests and exposed rock. Fresh water is not an obstacle for evaluation of the ground conditions, whereas measurements above salt water is limited to a water depth of in excess of 20 m. Steep topography is a challenge, but the problems can be reduced by reduced flying speed, and by flying all the lines «uphill». An appropriate area should be selected as landing and mobilization area, for example a sportsground, parking place or other flat, open areas far from trees, powerlines and other similar obstructions, see Figure 2.11.

Up to 300 km flylines can be gathered daily. This corresponds to an area of about 30 km^2, with line spacing of about 100 m. The sensor (antenna) of the AEM equipment is operated with a height of about 30 m above the ground surface, and is usually lifted by a helicopter. Since the method creates some public interest, it is important to give sufficient warning to the population of the neighbourhood through the local authorities. The helicopter company arrange permissions for flying with a hanging object, and also keep good contact with the aviation authorities during the operations.

Figure 2.11: AEM equipment (SkyTEM304), take-off at Vestfold University campus.

Geotechnical applications
The geotechnical applications are primarily:

- Investigate deposits of possible leached clays and silt
- Indicate depth to the bedrock surface
- Map possible slide hazard in rocks by identification of possible weak zones and failure planes in the ground
- Modelling of the soil and rock by integrating AEM with geological and geotechnical data

Limitations
Urban areas have a usually a significant amount of installations in the underground, infrastructure on the surface, buildings, fences and powerlines, which all result in inductive coupling and hence signal noise. A large part of these areas may not be covered by the AEM-measurements, since it is not allowed to fly over human beings and animals with a hanging object.
In such cases, some of the data have to deleted in the processing since they are heavily influenced by the noise.

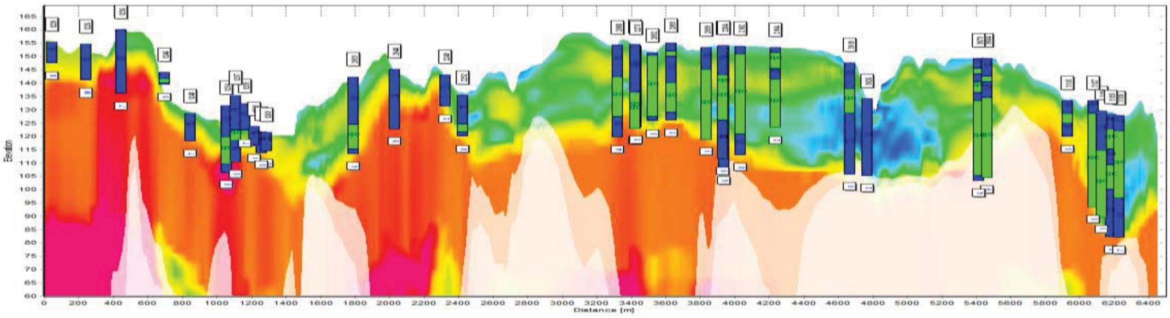


Figure 2.12: A 6.5 km long resistivity profile with rock control drillings (blue/green bars), illustrating how AEM can map the rock topography (yellow-red colours) along a road corridor (see also Enclosure C1).

AEM cannot be recommended for smaller projects, since it is relatively expensive to mobilize the system for a few kilometers of profiling. For larger projects, the cost per meter is however comparable to ERT and other surface based methods.

2.4 Vane testing

2.4.1 General

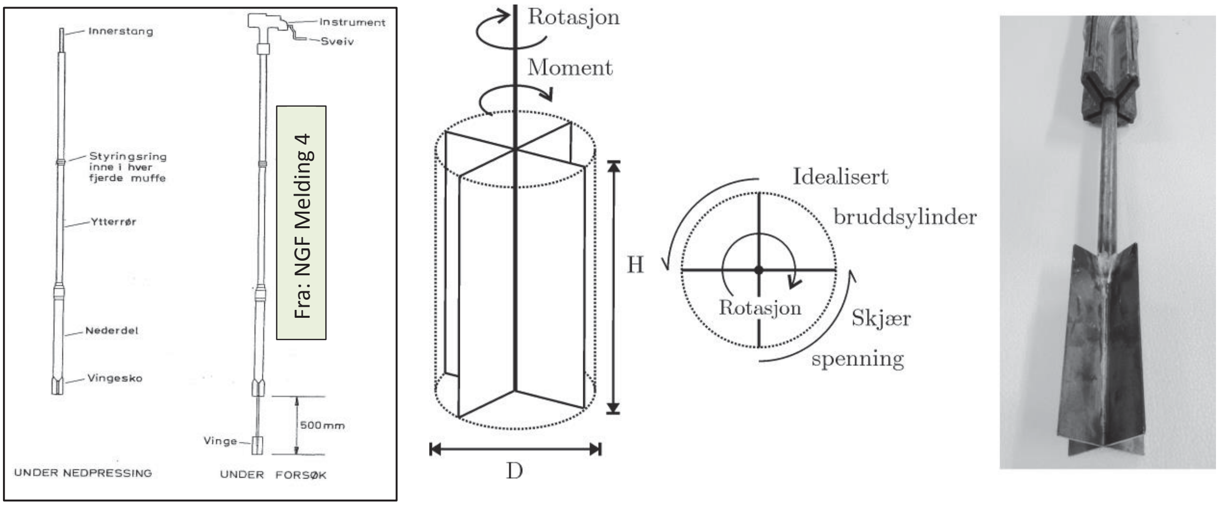
Vane testing can be used to determine the undrained shear strength in clays and clayey silts. Both undisturbed (c_{uv}) and remoulded shear strength (c_{rv}) can be measured. The vane is the only in situ test that can be used to determine the remoulded shear strength and hence the sensitivity ($S_t = c_{uv}/c_{rv}$) directly. Before the test, it must be verified by sounding that the soil is convenient for use of this method. When utilizing the results for evaluation of bearing capacity and stability, the vane test should not be the only test available.

2.4.2 Description of test equipment and procedures

A complete field vane equipment consists of a lower part with the vane protection shoe and the vane itself, a set of inner rods, outer rods and a recording instrument, see Figure 2.13. The vane is mounted on the inner rods and is protected by a vane shoe during penetration in the soil. Usually the vane consists of four rectangular plates, mounted in a cruciform shape. Most of the interpretation models are based on the assumption that the failure geometry can be approximated by a cylindrical surface.

The standard size for actual vanes for Norwegian conditions are:

> <u>Small vane (DxH): 55 x 110 mm</u>
> Recommended for strength range c_{uv} = 30 - 100 kN/m^2
>
> <u>Large vane (DxH): 65 x 130 mm</u>
> Recommended for strength range c_{uv} < 50 kN/m^2 and for measurement of remoulded shear strength c_{rv} in sensitive clay



a) b) c)

Figure 2.13 Illustration of vane test equipment.

a) Overview of vane equipment
b) Principal application of torque on the vane
c) Detail of vane and vane shoe

The vane test is carried out in depth intervals, usually one measurement per 0,5 or 1,0 m. Before the measurement, the vane system is pushed down to the level where the measurements should take place. Here, a gradually increasing torque is applied on the inserted vane, until the material adjacent to the vane reaches failure. The maximum torque is recorded, and enables determination of the undrained vane strength c_{uv}. The rotation rate close to and at failure shall be about 0.2°/sec. The test should reach failure in 1-3 minutes.

The remoulded shear strength (c_{rv}) is determined after at least 25 full, rapid rotations of the vane. Two recordings are made with rotation rates of 0,2°/second, and with the vane rotated 90° between each recording. The lowest value is used for reporting.

By using an electric field vane, one may record the whole mobilization curve for the torque versus the rotation angle of the vane. This can give valuable information of the material behaviour, in addition to the shear strength values.

The vane test is susceptible to heterogenities in the soil. If parts of the vane (side, top or base) is weaker or stronger, or if fragments of shells or stone interfere with the vane, this may influence the measured values significantly. It is hence recommended to carry out several tests to reduce this uncertainty.

Moreover, it is important that the level of the vane is fixed during the measurements. If the vane is sinking or lifted during the measurements, the measured torque may increase, since parts of the vane then will rotate in an undisturbed or partially disturbed material.

Vane equipment of different type or manufacture will not always give the same results. In Norway, a modified SGI-vane equipment has been frequently used, and most of the practical experience and results are associated with this equipment.

3 Recommended use of relevant methods – evaluation of possibilities and limitations

3.1 Conventional sounding methods

Rotary weight, rotary pressure and total sounding are using, directly or indirectly, the measured total penetration force as indicator of brittle materials. However, the remoulded shear strength c_r only depends on the rod friction. At the start of the test and in layers close to the surface the rod friction is small, and the point load is the dominating part of the penetration force. This is gradually changing as the drilling gets deeper, and at large depths, the rod friction is the dominating component. In homogenous clay profiles, the friction is largest near the tip unless a reduction in friction occurs due to the larger diameter of the drillbit. The friction in the top layers may be reduced by increasing penetration depths due to increased remoulding from the rod system. Some reduction of the friction may also happen due to expansion of the borehole or eccentric movement of the rods, particularly in friction soils.

On the other hand, water will drain from the remoulded zone during consolidation, which implies an increasing strength by time. When evaluating the total penetration force, it is usually considered that the named effects are negligible, and that variations in the penetration resistance due to changes in the clay texture are small. This is not always the case, particularly not in transition zones between the dry crust and other dense layers, but also with underlying soft or sensitive clay layers. The transition from silty or varved clays may also give erroneous interpretation of the ground conditions.

The rod friction is often the dominating component in sensitive materials, except at small penetration depths. It can hence be expected that a good correlation exists between the penetration measured on top of the rods and the remoulded shear strength of the clay. This correlation is however influenced by the diameter of the drillrod, the design of the tip, the ratio between the tip diameter and the rod diameter, the penetration principle (rotation, pressure, hammer blows) and the penetration rate. The correlation is also based on the assumption that the stroke during penetration lasts long enough to eliminate the thixotropic effects that occur during mounting of new rods.

Moreover, the detection of brittle materials may be influenced by a series of common features in the soil composition and layering, amongst them being:

- Laminated clays with sand- and silt lenses
- Brittle materials below a top layer with variable thickness
- Brittle materials below a top layer of coarse materials
- Loose, water saturated silt and sand
- Artesian pore pressure

In addition, the results are influenced by conceptual effects:

- Effect of flushing on underlying layers in a total sounding
- Effect of preconsolidation stress and natural variation of shear strength and stiffness by depth

These comments create a background for the recommendations given in the following.

3.1.1 Rotary weight sounding

Rotary weight sounding represents the simplest detection method selected in this study. The advantage of the method is that the rod system sinks for its own weight (included 100 kg) in soft and sensitive layers, at least for shallow depths. The lower the load is, the softer the material is expected to be. Figure 2.1 in Chapter 2.1.1 shows examples of interpretation of quick clay layers in different sounding profiles. However, this is not a failsafe indication since other materials may show a similar behaviour. This effect is also influenced by the depth of the soft layer.

The twisted tip results in a considerable remoulding of the material during penetration of the rod system. Since the diameter of the tip is larger than the rod diameter (ϕ35 mm > ϕ25 mm), the tip will cause a certain reduction of the friction between the rod and the surrounding clay.

In rotary weight sounding, the number of half turns and the weight on the rod system is recorded. This means that friction against the drill rods will become an increasing problem with depth, which may imply that thin, soft or sensitive layers may be hidden in the sounding profile. This effect will depend on the ground conditions in the upper layers, the thickness of the actual sensitive layer and if predrilling is used through the top layer. By predrilling, one may reduce this influence factor, and soft and sensitive layers may be more visible.

For details and interpretation procedures, reference is made to NGF Guideline 3. A summary of the detection principles, limitations and possibilities for this method is given in Table 3.1.

Table 3.1 Summary – detection of brittle materials from rotary weight sounding.

Detection principle	Positive features	Negative features
The rod system sinks under its own weight in soft, sensitive layers. This is visible in the sounding curve (penetration without rotation). The slope of the sounding curve may also be used.	Simple and cheap method. Can be used at sites where accessibility is limited, such as ravines and steep terrain. Simple detection principles.	Limited penetration in dense materials. The penetration is influenced by friction for increasing penetration depths (> 10 m). Cannot be used for verification of the bedrock surface.

3.1.2 Rotary pressure sounding

Rotary pressure sounding is performed with heavier and larger equipment than rotary weight sounding, and it is also a faster method to perform. The design of the twisted tip and the rate of rotation is adapted to the rate of penetration as the rods are penetrated into the soil. The remoulding of the soil and the relative expansion of the borehole is hence reduced. This implies that only a part of the rod friction is recorded as a vertical force.

For details and interpretation principles, reference is made to NGF Guideline 4, whereas a summary of typical sounding results is shown in Figure 3.1. The figure shows interpretation principles of brittle materials, where the recorded penetration force is used to determine the sensitivity of the material. The variation in sensitivity is identified by different slopes of the curve. Quick clays and very sensitive clays will give approximately vertical slope of the sounding curve, whereas low-sensitive clays shows an increase in penetration force with depth, approximately linear in homogeneous, non-sensitive layers.

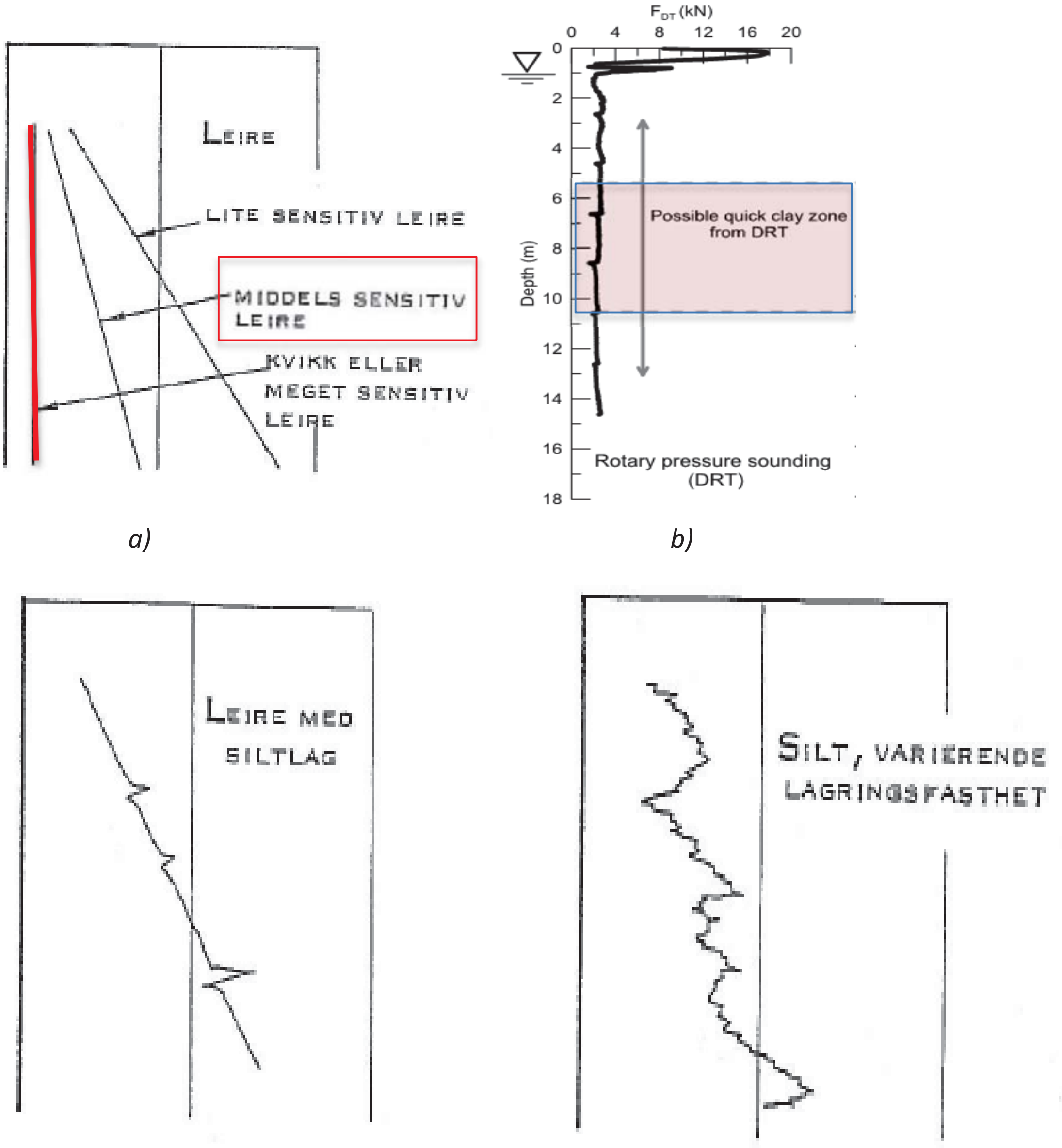
Detection of brittle materials from rotary pressure sounding is hence mainly based on the shape of the sounding curve, to a lesser degree the magnitude of the recorded penetration force. However, it may be worthwhile to consider the combination of magnitude and shape of the curve in some cases, particularly if the combination of low force and constant or declining sounding-resistance occur. An evaluation of the penetration force requires that the load cell on the drillrig is correctly calibrated.

In most soils, the increasing friction along the drillrods will result in an increasing penetration force with depth. In a very sensitive or quick clay the increase in friction is close to zero, if other conditions are kept unchanged. The influence of the sensitivity is hence explained by the fact that remoulded, sensitive soils give less contribution from friction to the penetration force since the remoulded soil behaves more or less like a liquid. Hence, no increase in penetration force will be noticed, resulting in the characteristic vertical curve signature in such clays.

In addition, the collapse behaviour at increasing shear strains will also result in a reduced contribution from the tip resistance, which in some cases will cause reduced resistance with depth (negative slope of the sounding curve).

However, it is sometimes seen that profiles with constant or reduced sounding resistance not necessarily is due to presence of sensitive or quick clay in the deposit. Several other features may cause similar behaviour, such as:

- Sounding in loose, water-saturated silt may give approximately constant sounding resistance during penetration due to collapse of the silt below the tip, and also very small contributions from friction. This is particularly the case for shallow deposits of loose silts.
- Transition zones from denser to looser, homogeneous layers of fine sand can also give sequences of reduced sounding resistance and smooth sounding curves that can be very similar to the signature of quick clays. Usually, the magnitude of the penetration force is somewhat larger than for sensitive clays.
- Thick layers of material with high organic content will normally yield very low penetration resistance and in some cases also a vertical sounding curve. If the organic matter is intact, the penetration force will usually increase with depth.
- Silty, leached clay containing frequent silt lenses may represent a situation where the clay layers are sensitive or quick, whereas the penetration resistance will increase with depth due to high friction in the silt layers.



a) b)

c) d)

Figure 3.1 Characteristic sounding profiles for rotary pressure sounding.

a) Principal detection of quick clay/sensitive clay
b) Example of profile in quick clay, Klett north test site
c) Typical sounding result, non-sensitive clay
d) Typical sounding profile, silt

A summary of detection principles, possibilities and limitations of the method is given in Table 3.2.

Table 3.2 Summary – detection of brittle materials from rotary pressure sounding.

Detection principle	Positive features	Negative features
Approximately vertical or negative slope of sounding curve. The magnitude of the penetration force can provide supplementary information. This requires correctly calibrated load cell on the drillrig.	Simple interpretation of the sounding-curve. Machine-based method, good capacity for normal sounding conditions. Reflects soft and sensitive layers in the ground.	The detection principle is influenced by several features, one of them being thick top layers with coarse materials (> 5 m). Cannot penetrate dense, stone rich layers and cannot be used for verification of the bedrock surface. Somewhat influenced by rod friction at larger penetration depths (> 10 m).

3.1.3 Total sounding

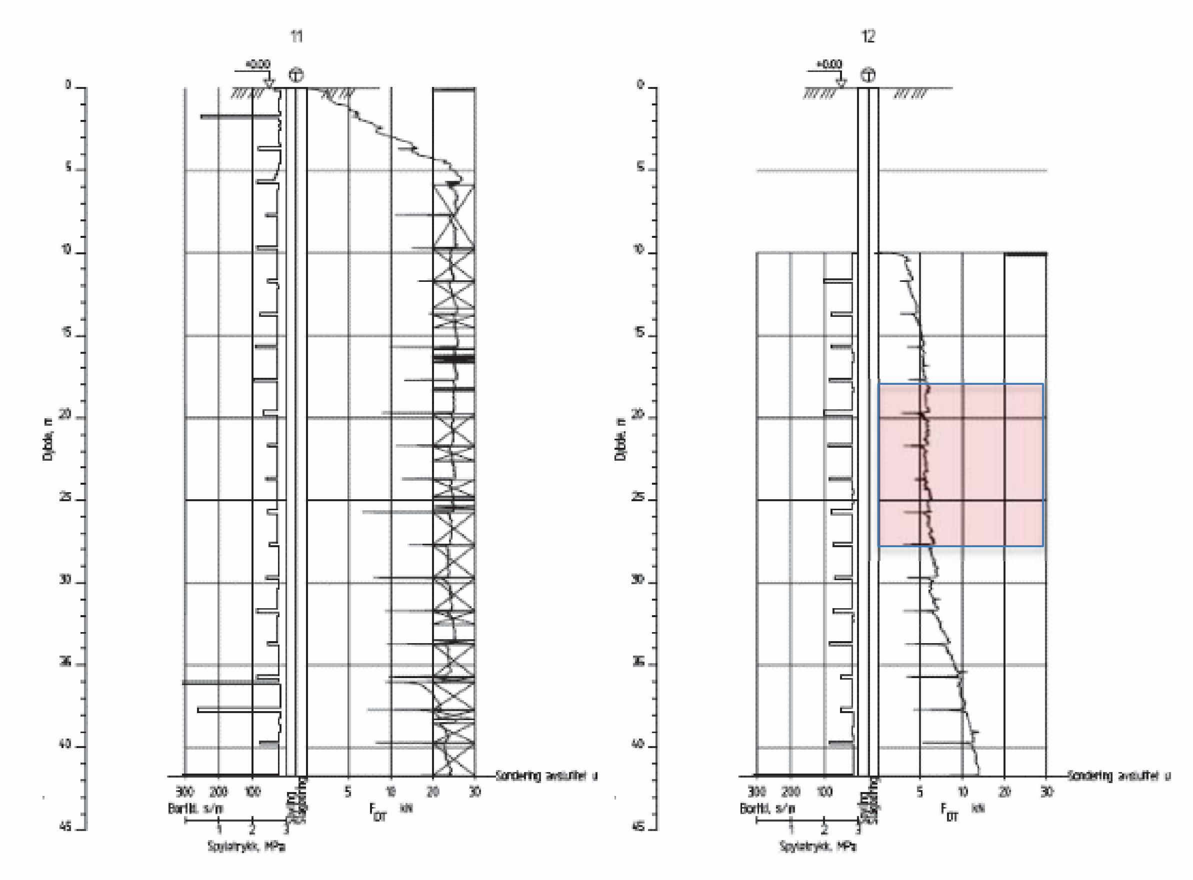
For details concerning equipment, test procedures and interpretation, reference is made to NGF Guideline 9.

Total sounding is basically performed with the same penetration and rotation rate as rotary pressure sounding, but the equipment is performed with larger diameter rods and a drillbit equipped with a return valve (ϕ57 mm/ϕ45 mm). The resolution of the drilling records is more or less similar to rotary pressure sounding, but the reduction in rod friction is assumed larger due to the increased diameter of the drillbit. This is positive for the penetration capacity, but may result in a less pronounced effect of the friction in brittle materials. The rotating drillbit will cause some remoulding of the surrounding soil masses, but this effect is uncertain.

Experiences from rotary pressure sounding are also the basis for interpretation of the rotary pressure mode in total sounding. The magnitude of the penetration force is usually similar to or somewhat bigger than in rotary pressure sounding. Rotary pressure sounding is hence regarded as a more sensitive method for detection of brittle materials, since it emphasizes the contributions from friction and shear during penetration of the drillrods. Reference is made to Chapter 3.1.2 for further explanation of the interpretation principles.

If flushing is used to penetrate dense layers, this will reduce the rod friction considerably above the level where flushing was terminated. The flushing is taking place with relatively high pressures, and may also influence the behaviour of the soils below the flushing level. This influence can result in lower strength and stiffness in the underlying soils, which in turn cause lower penetration resistance and a sounding profile that resembles that of quick clays. In such cases, it is important to consider if the total sounding was performed with flushing near the transition to softer layers.

Systematic studies of the maximum influence distance from flushing has not been carried out. The influence distance may depend on several features, both related to the ground conditions, the magnitude of the flushing pressure, the type of flushing medium (air/water) and the depth below the terrain surface. Pressure changes in clays will usually have an influence zone of about 5-7 times the diameter of the pressure source, which corresponds to about 25-35 cm in undisturbed clay. In general, use of air pressure will have a larger influence zone than water flushing. Another effect of water flushing is the improved lubrication of the rod system, which will influence the rod friction if drilling continues in the underlying clay.



a) b)

Figure 3.2 Example of the influence of pre-drilling through top layer in detection of quick clay.
(a) Without predrilling through 10 m top layer
(b) With predrilling through 10 m top layer
Red marking: Assumed quick clay layer from total sounding
Example from Flatåsen quick clay hazard zone, Trondheim, ref. Trondheim kommune report R-1622).

When deviations from the normal sounding procedure occur (standard rotation and penetration rates), the sounding profile cannot be interpreted by ordinary methods. In that case, one may predrill through the dense layers and then run the normal penetration procedure from the predrilling level. In this way, the sounding resistance is not influenced by the contribution from overlying top layers, and the sounding curve may be used to evaluate relative stiffness and sensitivity, as long as the standard test principles have been used.

When drilling through a dense, thick top layer, the friction in this layer may influence the sounding profile considerably. Figure 3.2 shows an example of sounding profiles with and without predrilling through a 10 m thick dense top layer. The results show that the quick clay layer appear reasonably clear after predrilling through the top layer (Figure 3.2 b), whereas it is hidden when the sounding starts from the surface without predrilling (Figure 3.2a). If layers of brittle materials are expected at a site, one should predrill through an occuring top layer to obtain detection of potential soft and sensitive underlying strata.

When ordinary penetration is combined with predrilling through top layers, the following procedure is proposed:

1. Set a new location at a minimum distance of 2 m from the first sounding profile used to assess the predrilling depth
2. Predrill down the requested depth and make a quick identification of the soil debris (recorded in the drilling log)
3. The total sounding is separated in two parts and is recorded in two raw-data files, for example A and B. A shall consist of the sounding results down to the predrilling depth and B from that level down to the termination depth. In this way, one may evaluate the effect of the overlying top layer.
4. The applied procedure should be described in the boring log so that it is easy to distinguish between the two soundings.

In such cases, It is necessary to perform two profiles, one with and one without predrilling. This requires more resources and is not applicable in all cases. It is hence important to evaluate the possible presence of quick and sensitive clays before the site investigation is started, based on previous information of the area.

A summary of detection principles, possibilities and limitations for this method is given in Table 3.3.

Table 3.3 Summary – detection of brittle materials from total sounding.

Detection principle	Positive features	Negative features
Approximately vertical or negative slope of the sounding curve. The magnitude of the penetration force can provide supplementary information. This requires correctly calibrated load cell on the drillrig. The detection principle is influenced by several factors.	Simple interpretation of the sounding-curve. Machine-based method, very good capacity for most sounding conditions. Can drill through dense, stone-rich layers and can also be used for verification of the bedrock surface.	Somewhat influenced by rod friction at larger penetration depths (> 10 m). Flushing with air may influence the sounding conditions below the drillbit. May give false impression of soft, sensitive layers beneath the flushing level. Less sensitive to friction- and shear contribution against the drillbit than rotary pressure sounding.

3.2 Cone penetration test with pore pressure measurements (CPTU)

CPTU has a great potential for detection of quick and sensitive layers since all measurements are carried out in the probe. The measurements are hence not influenced by the accumulated friction against the rod system. In addition, both mechanical cone resistance and sleeve friction is measured, and the pore pressure may to some extent capture the collapse mechanism in the penetrated soil.

3.2.1 Detection of quick or sensitive clay from CPTU

Detection of quick or sensitive clay from CPTU may be evaluated from the following results:

- *Net cone resistance (q_n) – sounding depth (z) (or effective overburden stress (σ_{vo}').*

  - Detection from net cone resistance q_n (or the cone resistance number $N_m = q_n/(\sigma_{vo}' + a)$), follows in principle the same guidelines as for interpretation of rotary pressure sounding (slope of the sounding profile)
- *Sleeve friction (f_s) or friction ratio ($R_f = f_s*100\ \% /q_n$) – sounding depth (z).*
  - Low values of the sleeve friction f_s (R_f, $R_{fu} < 2{,}0\ \%$) may indicate brittle materials
  - In several of the sites studied, the f_s-profile drops off at the top of the quick clay layer
- *Pore pressure ratio ($B_q = \Delta u/q_n$) – sounding depth (z).*
  - High values of the pore pressure ratio $B_q > 1{,}0$ often indicate quick or very sensitive clays
- *Use of identification charts for detection of sensitive materials*
  - Combination of dimensionless ratios for cone resistance (N_m, Q), pore pressure (B_q) and friction (R_f) can classify brittle materials.

Note: One example from a quick clay deposit at Klett test site is shown in Figure 3.3. Interpretation of the soil behaviour is based on a combination of measured and derived parameters, and identification charts are often used to classify the materials.

Despite the obvious potential, mixed experiences exist with CPTU for detection of brittle materials. The reason may be that the sounding results are influenced by several factors that are not related to the clay being sensitive or not. These factors are discussed in the following.

Sleeve friction f_s:

A completely remoulded quick clay has a remoulded shear strength of $c_{ur} < 0{,}5$ kPa. Hence, the material is close to a liquid after full remoulding of the soil structure. In CPTU, this should imply very small mobilized friction along the friction sleeve, assuming that the clay becomes completely remoulded by the first penetration of the probe. However, analyses of a series of CPTU-profiles show that the sleeve friction can be high after the first penetration of quick or very sensitive clays. This is often the case in silty clays, where the material requires several repeated penetration cycles of the probe before full remoulding is obtained. Tests with special probes show that as much as 5-10 repetitions may be needed to obtain full remoulding. After these repetitions, there is good agreement with the residual friction in CPTU and the remoulded shear strength in a laboratory fall cone tests.

Friction ratio R_f:

In normally consolidated clays the friction ratio $R_f = f_s*100\ \%/q_n$ is usually in the range of 0 % to 2 %, but large variations occur in both directions. It may also happen that non-sensitive clays exhibits values in the same order of magnitude, probably due to inaccurate measurements and lacking corrections of measured sleeve friction for pore pressure effects.

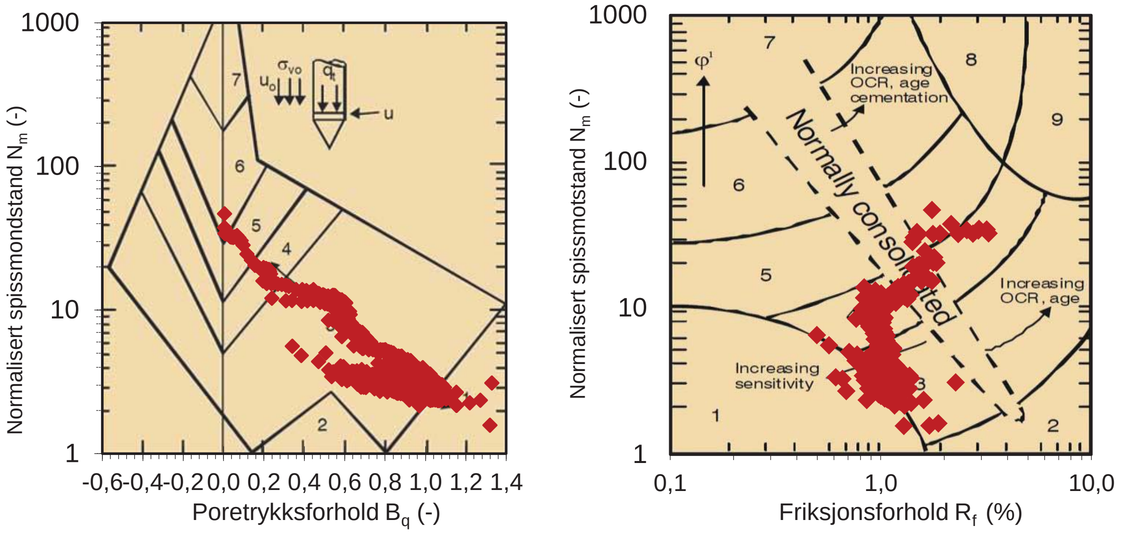
Net cone resistance q_n:

The effect of constant or gradually decreasing penetration resistance is characteristic for several types of soundings in quick or sensitive clays. Accordingly, one should expect that the net cone resistance q_n in a CPTU shows the same tendency. This appears however not to be the case and is not recommended as a valid criterion, probably because that the CPTU-probe is not rotated during penetration.

Cone resistance number N_m:

The dimensionless cone resistance number N_m (~Q, where Q is defined without attraction, but otherwise similar to N_m) is found to be a better indicator of brittle materials than the net cone resistance q_n. In brittle materials, the N_m-profile shows no increase by depth, rather a slight reduction. In sensitive, one will often observe N_m – values < ca. 4.

The interpreted parameter may however be slightly influenced by depth effects.



a) b)

Figure 3.3 Existing identification charts for soil classification, Robertson et al (1990).
a) Pore pressure ratio B_q, b) Friction ratio R_f.
Results from Klett south test site in quick clay (ref. Multiconsult report MC 415559-RIG-RAP003)

Pore pressure ratio B_q:

By penetrating a CPTU probe into the ground, a mass displacement with large strains occur around the probe. These stress and strain changes causes a change in the pore pressure in the influenced zone.

The pore pressure ratio $B_{q2} = \Delta u_2/q_n$ may be an efficient indicator of quick and sensitive normally consolidated clays, where the dilatancy effect in the soil behind the conical tip is limited. The pore pressure response in the compression zone beneath the conical tip (u_1) is generally higher as the one behind the conical tip (u_2), depending on the soil type. In quick clays, $B_q \geq 1,0$ is common due to the collapsible behaviour at failure, associated with large excess pore pressures.

In stiffer, overconsolidated quick clays, the B_{q2} - values are usually significantly lower, often between 0,6 and 0,9, depending on the overconsolidation ratio. The shear stress induced pore pressure behind the conical tip will contribute less to the total pore pressure build-up due to positive dilatancy. The measured pore pressure behind the tip hence becomes somewhat less than the pore pressures in the compression zone beneath the tip (u_1). Here, the dilatancy effect is less due to a lower shear stress induced contribution and larger contributions from compression stresses. The dilatancy properties of a clay hence have an important influence on the measured pore pressure, and the pore pressure ratio is consequently not a unique identification parameter for classification of brittle materials. It is hence an advantage to measure or correlate the tip pore pressure (u_1) for identification of brittle materials.

The experiences with detection of brittle materials directly from CPTU-measurements have as previously described been mixed, and today no unique, sufficiently documented method for determination of quick and sensitive clay from CPTU. The parameters listed above do not take the special behaviour of brittle materials into account, such as sensitivity, necessary remoulding energy and stress history.

As a result of the detection study in NIFS, new and alternative methods of interpretation have been introduced, such as:

- ✓ Use of total penetration force and rod friction for the rod system

- ✓ Development of new identification diagrams based on the following revised, dimensionless ratios:
  - Use of revised cone resistance number N_{mc} (based on preconsolidation stress)
  - Use of revised pore pressure ratio B_{q1} (tip pressure)

The new approaches are described in further details in the following chapters.

3.2.1.1 Use of revised cone resistance number N_{mc}

The cone resistance number N_m appears to be an efficient indicator of brittle materials, determined from the slope of the N_m-curve versus depth. The cone resistance number is defined as (see e.g. Sandven, 1990):

$$N_m = q_n/(\sigma_{vo}' + a) \qquad (3.1)$$

where:

σ_{vo}' = effective overburden stress (present)

a = attraction (reduced effect by depth, small influence for z > 5 m)

In this definition, the present effective overburden stress σ_{vo}' is used as the reference stress. It is however more appropriate to use the preconsolidation stress σ_c' as reference, due to its influence on the material behaviour. This leads to the revised expression:

$$N_{mc} = q_n/(\sigma_A' + a) \qquad (3.2)$$

where:

σ_A' = reference stress (see equation 3.3)

To emphasize the preconsolidation stress, and also account for swelling effects of the material, the expression shown in Equation 3.3 is used as reference stress σ'_A. Equation 3.3 is similar to the expression used in the SHANSEP-approach (Ladd & Foott, 1974), where the stress exponent **m** accounts for the effect of unloading and swelling of the sediment. The way this expression is outlined, it is possible to adjust the effect of the overconsolidation, through the choice of the stress exponent **m:**

$$\sigma'_A = \sigma'^{\,m}_c \cdot \sigma'^{\,(1-m)}_{vo} \qquad (3.3)$$

where:

σ_c' = preconsolidation stress

σ_{vo}' = effective overburden stress

m = stress exponent accounting for swelling effects ($0 < m < 1,0$)

The preconsolidation stress shows a different variation compared to σ_{vo}', and may give a more correct impression of the material properties and the N_{mc}-variation with depth. This requires reliable values of the preconsolidation stress σ_c' so that a σ_c' – z profile can be established. The stress exponent m is derived from empirical values of the active undrained shear strength in Norwegian clays, with m being in the order of 0,7-0,8. The preconsolidation stress σ_c' hence becomes a very important parameter, and it is necessary to determine this parameter with some accuracy. At the same time, an exponent value of $m < 1,0$ will partly compensate for possible errors in the estimates of σ_c' through the mathematical formulations.

The preconsolidation stress should primarily be determined from oedometer test data, from the known topography and previous terrain level, otherwise from independent interpretation of CPTU data. Empirical relations between the overconsolidation ratio OCR and the pore pressure distribution around the probe can also be used (see e.g. Sully et al, 1988).

The revised cone resistance number N_{mc} is recommended for use in new identification charts for CPTU-data, together with the revised tip pore pressure ratio B_{q1}, see Figure 3.4.

3.2.1.2 Use of revised pore pressure ratio B_{q1}

Since the pore pressure ratio B_q to some extent is influenced by the overconsolidation ratio OCR and the dilatancy properties, it is natural to use this relationship for the revised tip pore pressure ratio B_{q1}. This can hence be expressed in the following way:

$$B_{q1} = (u_1-u_o)/(q_n) = (k_{clay}*u_2-u_o)/q_n \tag{3.4}$$

where:

k_{clay} = experience based correction factor expressing the ratio between the pore pressure at various locations on the probe (see Sandven (1990)):

Soft NC-clay:	k = 1,25
Medium soft clay, low OCR:	k = 1,50
Dense OC-clay, high OCR:	k = 1,90

The following relationship can be used to estimate u_1 when u_2 is measured (Sully et al, 1988), see Figure 2.5 for definition of u_1:

$$u_1 = u_2 + u_o*(OCR-0,66)/1,43 \tag{3.5}$$

where:

u_1 = pore pressure at the conical tip (u_1 usually > u_2)
u_2 = pore pressure at reference level behind conical tip
u_o = in situ pore pressure before penetration
OCR = overconsolidation ratio (= σ_c'/σ_{vo}')

This revised pore pressure ratio contributes to an improved approach for identification of sensitive and quick clay from new identification charts. The combination of N_{mc} and B_{q1} is used in a simple identification chart for sensitive clays, see Figure 3.3 and Table 3.4.

3.2.1.3 Use of revised friction ratio R_{fu}

Interpretation of the undrained shear strength from CPTU can either be based on the corrected cone resistance q_t or the excess pore pressure Δu_2. In soft and brittle materials, the pore pressure based interpretation is usually the most reliable, provided that the pore pressure recording system is sufficiently saturated. It is hence suggested to express the friction ratio in terms of the excess pore pressure u_1 (alternatively u_2) instead of the net cone resistance q_n in Equation 3.5, see Figure 3.5.

This formulation has the added effect that materials with distinct differences in pore pressure response becomes easier to classify. The alternative friction ratio is formulated as follows:

$$R_{fu} = f_s * 100\ \% / \Delta u_1 \qquad (3.5)$$

where:

f_s = sleeve friction (corrected value should be used)
Δu_1 = u_1-u_o, excess pore pressure at conical tip
u_o = in situ pore pressure before penetration

This relationship gives a collection of data with considerably less scatter compared to the classical definition.

The sleeve friction is however an uncertain parameter to use for detection of quick clays for the reasons discussed earlier in this chapter. This will also be valid for all expressions where the sleeve friction is included. The revised friction ratio nevertheless gives reasonably good classification of brittle materials.

3.2.1.4 Resistivity ρ

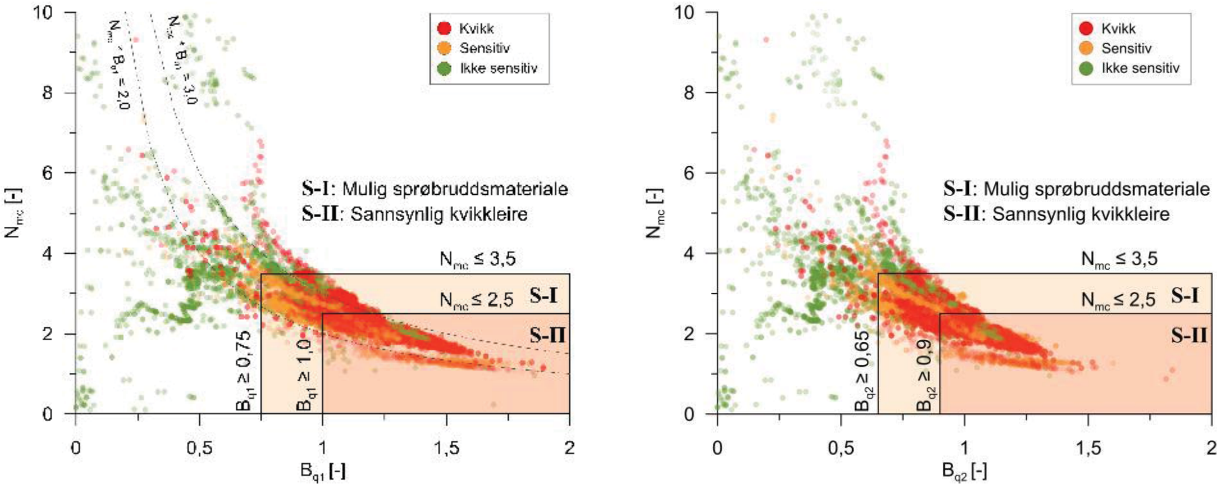
In this study, it has been evaluated if the resistivity can be used as a classification parameter in combination with other parameters, such as N_{mc}. This has been done for all test sites included in this report. The range of resistivity values for classification of possible brittle materials span from 10-100 Ωm, which is considered a wide range for a unique classification. There are also some leached, non-sensitive clays within this range. For classification purposes, the resistivity is not particularly well suited as a property for classification of brittle materials. The resistivity will however still be an important supplement together with other CPTU-parameters.

3.2.2 New identification charts

In the new identification charts for brittle materials, it is suggested to use a combination of N_{mc} and B_{q1}. By plotting data from all the test sites selected in this study, a relatively clear identification of layers with quick and sensitive clays is obtained. The charts, including classification criteria for quick clays and brittle materials, are shown in Figure 3.5.

The following classification criteria are suggested, based on the results in this study:

- $N_{mc} \leq 3{,}5$ and $B_{q1} \geq 0{,}75$: Possibly brittle material
- $N_{mc} \leq 2{,}5$ and $B_{q1} \geq 1{,}00$: Most likely quick clay



a) *b)*

Figure 3.4 Proposed and recommended identification charts for detection of brittle materials.
a) Based on the interpretation factor N_{mc} and revised pore pressure ratio B_{q1},
b) Based on the interpretation factor N_{mc} and the reference pore pressure ratio B_{q2}.

Compared to the identification charts developed by Robertson et al (1990), showing N_m (~Q) versus B_{q2}, an alternative combination of N_{mc} versus B_{q1} gives a more correct classification of brittle materials. The collection of data points is stretched along the axes, and it becomes simpler to distinguish between different material responses. In Figure 3.4a, limits for classification of brittle materials and quick clays are drawn. In the data sets, there are certainly some discrepancies, but for most test sites very good agreement is obtained.

For most CPTU-probes, the pore pressure u_1 is not measured and only the pore pressure behind the tip u_2 is known. However, several relationships between u_1 and u_2 based on OCR have been published, based on real measurements in various clays. Such a relation (Sully et al, 1988) is used for the data in Figure 3.4a. This approach represents some uncertainty due to the utilized empirical relationships, and it may hence be relevant to use B_{q2}, since this pore pressure ratio is based on measured pore pressures. Such a classification is shown in Figure 3.4b, where the following classification criteria are recommended:

- $N_{mc} \leq 3,5$ and $B_{q2} \geq 0,65$: Possibly brittle material
- $N_{mc} \leq 2,5$ and $B_{q2} \geq 0,90$: Most likely quick clay

Compared to use of B_{q1}, B_{q2} in Figure 3.4b gives less stretching of the test results along the horizontal axis and hence somewhat more unclear limits between different material behaviour.

The tendency in these data sets is clear, emphasizing the connection between these two parameters; a high B_{q1} value corresponds to a low N_{mc}. These two parameters reveal the same phenomenon, depending on the failure conditions and the structural collapse in brittle materials. Furthermore, there is also a clear connection between B_q and OCR. At the same time, OCR is included in the expression for N_{mc}. There is hence a relation between B_{q1} and N_{mc} which mathematically gives values of $N_{mc} * B_{q1}$ in the order of 1,8-3,2 for sensitive and quick clays.

The relationship between B_{q1} and N_{mc} implies that N_{mc} alone can be a good classification parameter. This principle is used in Figure 3.5, where N_{mc} is plotted versus the friction ratio R_{fu} for all test sites. As previously discussed, the interpretation of sleeve shows some scatter, which is also revealed in the classification in the $N_{mc} – B_{q1(2)}$ in Figure 3.4.

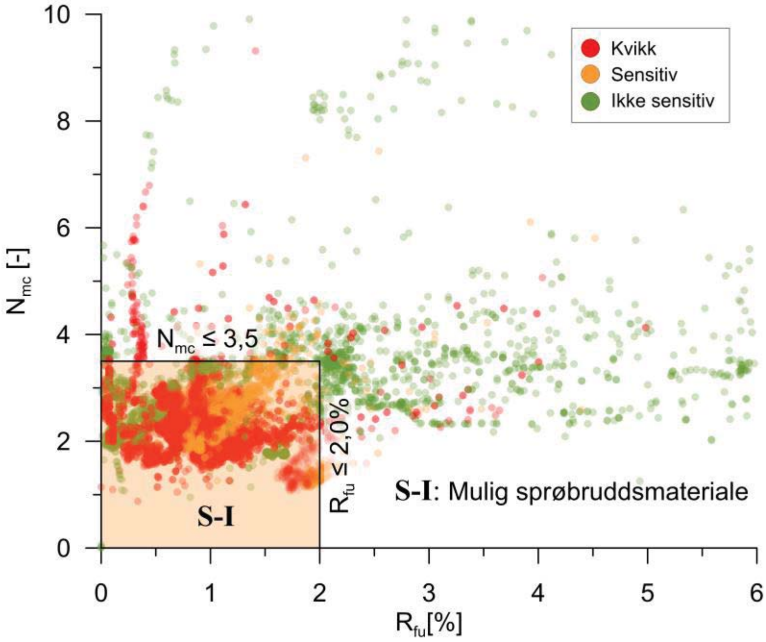


Figure 3.5 Proposed new identification chart for detection of brittle materials, based on the revised cone resistance number N_{mc} and the pore pressure based friction ratio R_{fu}.

However, it is a clear trend that brittle materials show low N_{mc}– values, but also low R_{fu} – values. Based on this, the following classification is suggested:

- N_{mc} ≤ 3,5 and R_{fu} ≤ 2,0%: Possible brittle material

For classification of brittle materials it is recommended to evaluate all available indicators. Conventional sounding profiles, together with depth profiles of N_{mc} and B_{q1}, are important in this respect. The proposed classification diagrams should be considered as a supplement to this and not a substitute.

Table 3.4. Value range for the classification parameters N_{mc}, B_{q1} and R_{fu} in brittle materials (quick and sensitive clays).

Parameter	*Value range for quick clay*	*Value range for sensitive clay*
$N_{mc} = q_n/(\sigma_A' + a)$ (-)	1 - 2,5	2,5 - 3,5
$B_{q1} = \Delta u_1/q_n$ (-)	1 - 2	0,75 – 2,0
$B_{q2} = \Delta u_2/q_n$ (-)	1 - 2	0,60 – 1,80
$R_{fu} = f_s/\Delta u_1$ (%)	0 – 2,0	0 – 2,0

3.2.3 Use of rod friction for detection of brittle materials

After penetration of the CPTU-probe, the sleeve friction may not represent a fully remoulded material, which means that the evaluation of quick clay status from the sleeve friction is difficult (f_s). The rod friction will however represent remoulded conditions along the drill-string, according to the continued penetration of the rods into the ground.

The total penetration force is usually not interpreted in a conventional CPTU. It is however easy to adapt the data acquisition system for this purpose, and the procedure does not require added time in the investigation. It is hence recommended to record the total penetration force routinely in a CPTU.

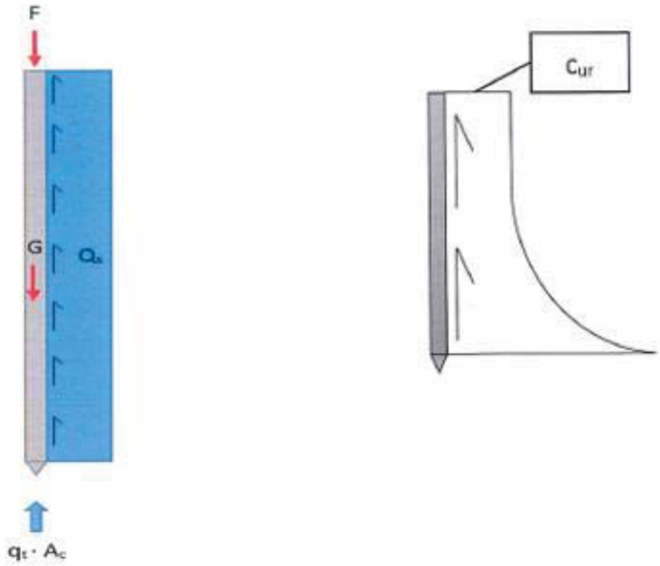


Figure 3.6 Principal determination of rod friction Q_s (Hundal (2014)).

In the interpretation, the weight of the drillrods and the tip force is subtracted from the total thrust, see Figure 3.6. The total rod friction Q_s can then be determined as a function of penetration depth, as shown in Equation 3.6:

$$Q_s = F + G - q_t{*}A_c \tag{3.6}$$

where:
F = Total penetration force (kN)
G = Weight of drillrod (N)
q_t = Corrected cone resistance from CPTU (kN/m^2)
Q_s = Mobilized rod friction (kN)
A_c = Cross-sectional area for CPTU probe (mm^2)

After continuous penetration of the rods, the remoulding of the materials will gradually become more complete along the drillrods. The friction may be determined as the average friction along the drillrods, but it will also possible to determine the increase in friction per meter drillrod. The latter approach should however be used with some caution. It is actually the total friction that is measured, and the friction at a given depth may change along the full length of the drill-string during penetration. If one try to address the contribution to the friction at a specific depth, the result can be dominated by a reduction in friction at another depth.

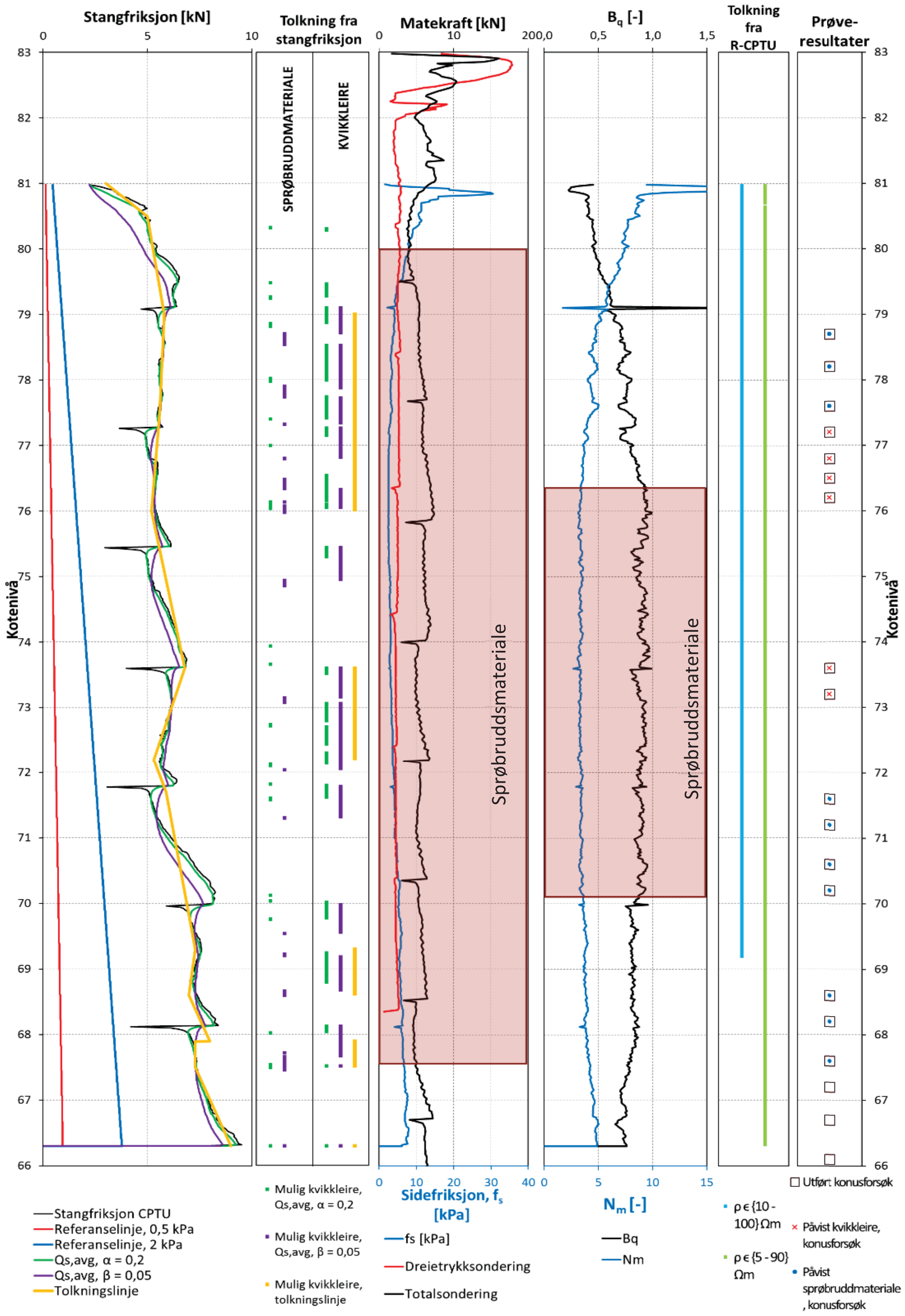


Figure 3.7 Example of summary of results – interpreted rod friction. Test site Esp, Byneset (Hundal, 2014).

The curve for the calculated friction can be determined by a line corresponding to a computed, evenly distributed friction of 2,0 kPa friction. According to the Norwegian guidelines (NVE 7/2014), this corresponds to the higher limit of remoulded shear strength in brittle materials. For quick clays, the slope of the friction force Q should be less than the slope for a reference line corresponding to 0,5 kPa sleeve friction (red reference line in Figure 3.7). For calculation of the slope, it is important to consider the used rod diameter. As an example, a rod diameter of ϕ36 mm (CPTU rods) will imply that quick clays are interpreted for curves with a friction gradient lower than 55 N/m.

In many cases, a friction reduction ring is placed behind the CPTU-probe. This contributes to increased remoulding and probably also reduced interface contact between rod and soil. This is also the case in R-CPTU if the resistivity module has larger diameter than the drillrods. The effect of this increased diameter on the rod friction is not fully investigated.

The detection of brittle materials from calculated rod friction has been carried out on a number of test sites in this study. The results indicate that layers of brittle materials can be detected, but there is a slight overestimation of the thickness of these layers compared to classification from laboratory tests. Similar experiences were found in the Swedish Göta älv project.

An example of the interpretation in quick clay is shown in Figure 3.7 (Hundal, 2014). In the figure, CPTU data are compared to results from rotary pressure sounding, total sounding and falling cone tests from laboratory tests.

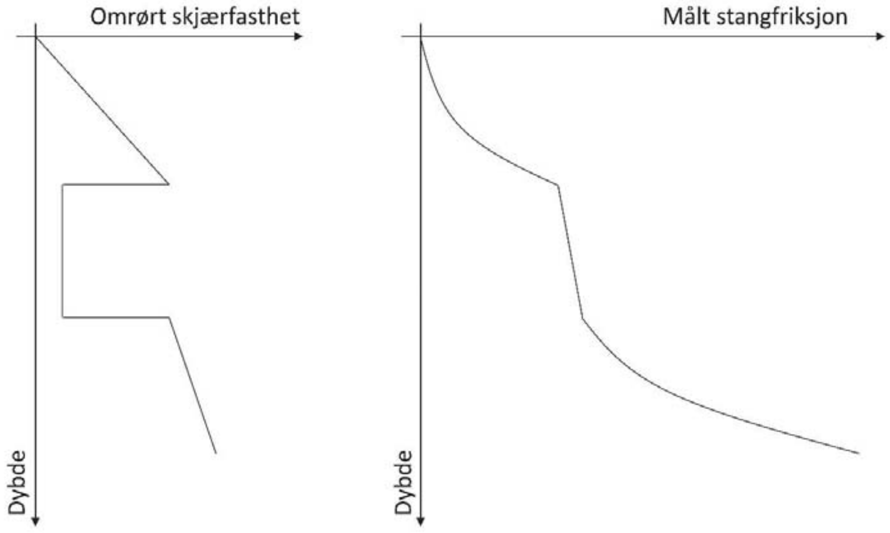


Figure 3.8 Effect of ground conditions on interpreted rod friction.

The overestimation in this approach is due to one major weakness of this method, where the information is based on the average friction along the drillrods. For ideal ground conditions, the interpretation is however simple, as examplified in Figure 3.8.

If the remoulded shear strength increases with depth, the average rod friction increases exponentially. In the layer with low and constant remoulded shear strength, a linearly increasing rod friction is interpreted. The slope of this line corresponds to the remoulded shear strength in this layer, and the interpretation is assumed to be correct.

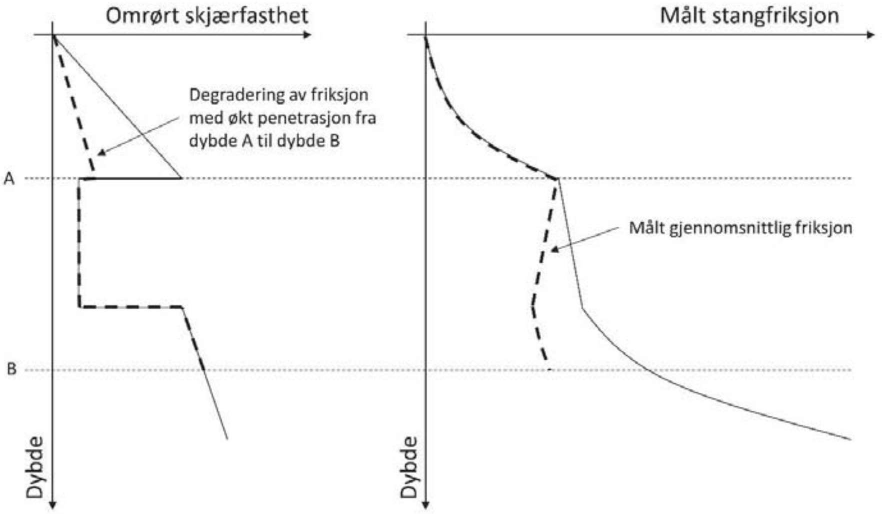


Figure 3.9 Effect of ground conditions on interpreted rod friction, where increased penetration leads to a loss of friction in the top layer.

The challenge is however that the ground conditions will resemble those shown in Figure 3.9. As the rod system penetrates the upper layer, the friction will be reduced. This can be due to several factors, amongst them being increased remoulding. The result will be that the average friction will show a negative slope in the weak layer and an increased friction in the denser layer. Loss of friction in the upper layer hence causes reduced slope on a curve that shows average friction versus depth.

A negative slope is a clear indication of such a mechanism. For interpretation of brittle materials, a low increase in rod friction can hence be due to a loss of friction in the upper layer or the fact that there exists low friction in a layer of brittle material at the actual penetration depth. This can lead to an overestimation of the quick clay extension.

Another challenge with the method are thixotropic effects during change of rods. The clay may stick to the rods in the waiting time, with resulting higher friction than the remoulded shear strength should represent.

Table 3.5 Summary – detection of brittle materials from cone penetration tests with pore pressure measurements (CPTU).

Detection principle	Positive features	Negative features
Values for the pore pressure ratio B_q, primarily with estimated or measured pore pressure at the tip of the cone (u_1). Profile of net cone resistance q_n or cone resistance number N_m. Sleeve friction and/or rod friction.	Enable detection after several principles: Cone resistance, pore pressures and friction. Very accurate measurements gives a good basis for further processing. Measurements independent of depth and accumulated rod friction.	Relatively complicated sounding method. Requires good skills and competence for operator to obtain good results. Measured data and identification parameters influenced by several factors. Cannot be used for sounding in dense and stone-rich deposits, predrilling through such layers is required.

3.2.4 Summary

By the new methods described in the previous chapters, the potential for interpretation of brittle materials from CPTU has been improved. Even if none of the methods are failsafe, they will extend the interpretation repertoire compared to previous methodology.

A summary of detection principles, possibilities and limitations with this method is given in Table 3.5.

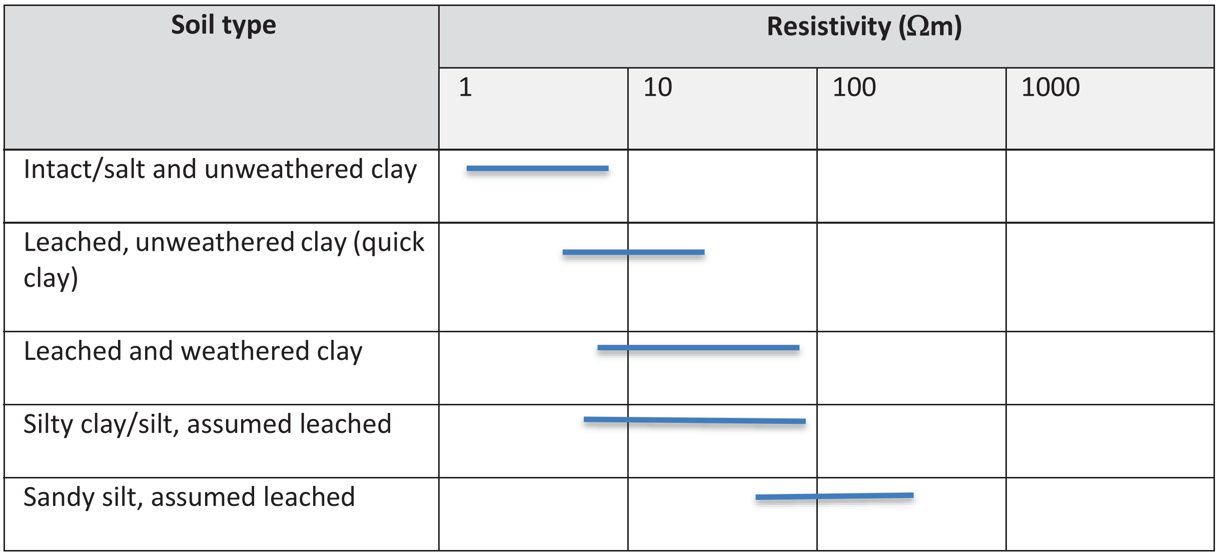
3.3 Resistivity measurements

The resistivity is a measure of the ability of soils to conduct electrical current. The resistivity ρ (Ωm) is defined by the electric field potential E (V/m) over the current density J (A/m^2)m, and can be computed from the electrical current, a geometry factor and the measured potential. The measured resistivity gives information about the soil layers, and may in this context indicate the salt content in the ground water and the level of leaching in marine clays. The resistivity computed from the measurements is an apparent resistivity, which will be identical to the real resistivity in the ground if the material is homogeneous. If the ground is inhomogeneous, the apparent resistivity is determined from a weighted average of the resistivity in all influenced layers.

Tables 3.6 a and b summarizes the resistivity in various geological materials, based on Norwegian experiences. It is emphasized that local site specific values may differ from the tabulated values.

Table 3.6. Resistivity in various geological materials.

a: After Rømoen et al (2010).



Soil type	Resistivity (Ωm)			
	1	10	100	1000
Intact/salt and unweathered clay				
Leached, unweathered clay (quick clay)				
Leached and weathered clay				
Silty clay/silt, assumed leached				
Sandy silt, assumed leached				

b: After Solberg et al (2008).

Soil type	Resistivity (Ωm)	Remarks
Salt, marine clay	1 – 20	
Leached clay, possible quick clay	20 – 90	Note: This can also be silty materials or clay that has passed the quick stage
Dry crust, coarse materials, sand and gravel	70 – 300	
Silt, saturated	50- 200	
Sand, saturated	200 - 1000	
Rock	Several 1000	

<u>Remarks:</u> Leached clay is a material with low salt content that has not been remoulded. Data from leached and re-consolidated clay after a quick clay slide has not been systematically collected. It is expected that such clays have resistivity values similar to those of leached clays. These clays may also be subjected to oxidation processes over time.

Since the grain skeleton and the number of clay particles influence the resistivity, a fat clay with high clay content will have lower resistivity after leaching, compared to a lean, silty clay. This may explain why the fatter Swedish clays show somewhat lower resistivity values than Norwegian clays. This also makes it easier to distinguish between salt and leached clays for lean clays.

In soils, the pore water is the primary conductor, whereas minerals and rock fragments have poorer conductivity. Due to this, the amount of pore water and the composition of ions will significantly influence the resistivity. In clays, this can be utilised as an indication of leaching. However, the resistivity also depends on several other factors, such as clay content, water content, grain size distribution, organic content, mineralogical composition and temperature.

3.3.1 Downhole measurements with resistivity probe (R-CPTU)

R-CPTU reveals a combination of different physical properties of the soil, such as mechanical stiffness (cone resistance number), hydraulic properties (pore pressure ratio) and resistivity. A combination of these parameters is assumed to give a stronger indication of brittle materials than any of the parameters alone.

When the R-CPTU sounding is carried out, records of corrected cone resistance q_t, pore pressure u_2, sleeve friction f_s and measured resistivity (Ωm) and/or conductivity has been made (mS/m), all as a function of depth. The resistivity can be presented in linear or logarithmic scale.

For presentation and interpretation of results from R-CPTU, it is convenient to gather data from several test methods and plot the results parallel to each other, see Figure 3.10. Examples of relevant test methods can be conventional soundings, electric field vane tests (EFVT), 2D resistivity profiles (ERT/AEM) and laboratory test results. If this is done, it is far easier to evaluate the variations in ground conditions, where the results may indicate layers of brittle materials.

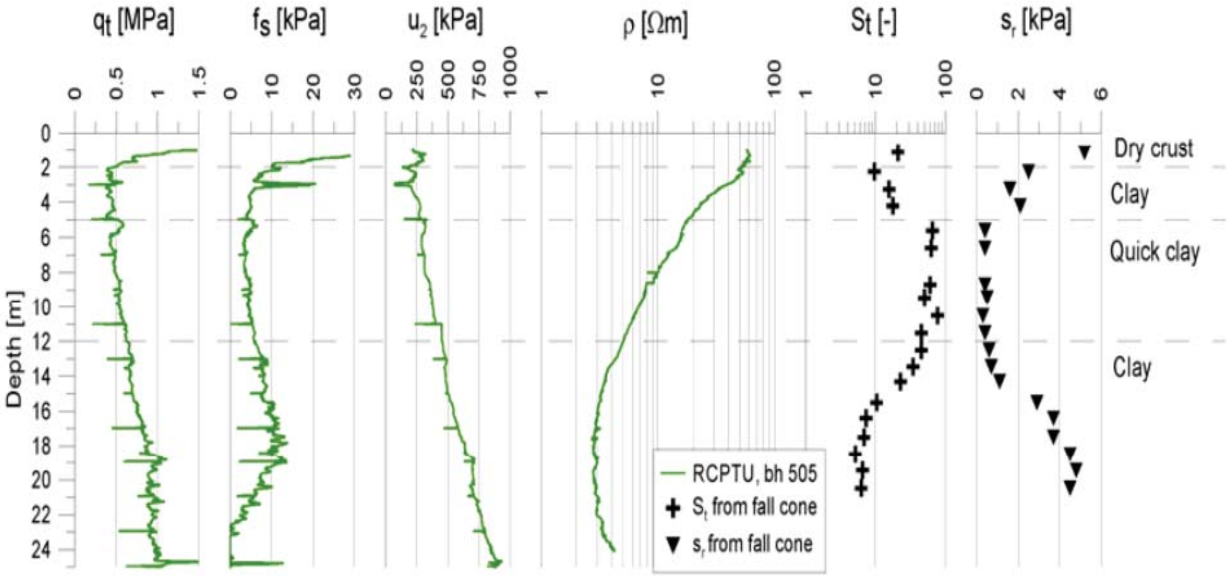


Figure 3.10 Results from R-CPTU soundings at test site Smørgrav, compared to laboratory test data (Rømoen et al, 2010).

Table 3.7 Summary – detection of brittle materials from cone penetration tests with resistivity measurements (R-CPTU).

Detection principle	Positive features	Negative features
Value of pore pressure ratio B_q, primarily with estimated or measured pore pressure at the tip of the cone (u_1).	Enable detection after several principles: Cone resistance, pore pressures and friction.	Resistivity for leached clays show large scatter, overlaps values in other materials.
Profile of net cone resistance q_n or cone resistance number N_m (Q).	Very accurate measurements gives a good basis for further processing.	Measured data and identification parameters influenced by several factors.
Measured resistivity compared to experienced values for leached clay. May also be compared to data from ERT and AEM if available.	Measurements independent of depth and accumulated rod friction. Continuous measurements by depth.	Cannot be used for sounding in dense and stone-rich deposits, predrilling through such layers is required.

3.3.2 Electrical resistivity tomography (ERT)

Resistivity measurements at the terrain surface (Electrical Resistivity Tomography ERT) give an overview of the resistivity along profiles that can be several hundred meters long, with a depth range of several tens of meters. Primarily, the method is used to get an overview of the distribution and homogeneity of the sediments. Since the resistivity of the clay primarily is determined by the salt content, a resistivity model can be used to evaluate the extension of potential layers of leached material. This information can be used to evaluate how far a possible retrogressive quick clay slides can develop, and by that also the maximum run-out distance of the slide debris. If the results from the ERT measurements are available before the geotechnical borings, ERT can be used for planning the locations of geotechnical.

If there are existing borings along an ERT-profile, the boring results can be used to establish correlations with the soil resistivity, and also to define the extension of sensitive layers (see Figure 3.11).

In many cases, ERT can be used in steep areas where drillrigs cannot access, for example in dense forests, in steep terrain, and for detection of clay beneath dense layers that cannot be penetrated by geotechnical sounding equipment. The method is also well suited for investigation of large areas or along planned road or railway lines in a more cost-efficient way than with geotechnical borings alone.

The two main challenges and limitation with the ERT method are:

(a) The resistivity is not a unique indication of leached clay. Increased resistivity can be caused by a lower salt content, but also by a high silt content. It is hence recommended to always "calibrate" the resistivity model by geotechnical borings, ideally with an R-CPTU. Results from this sounding can be used to establish an empirical relationship between resistivity and sensitivity for the investigated site. Leached, sensitive clays generally have a higher resistivity than less leached and less sensitive clay. However, examples exist where brittle materials have been found in layers with lower resistivity.

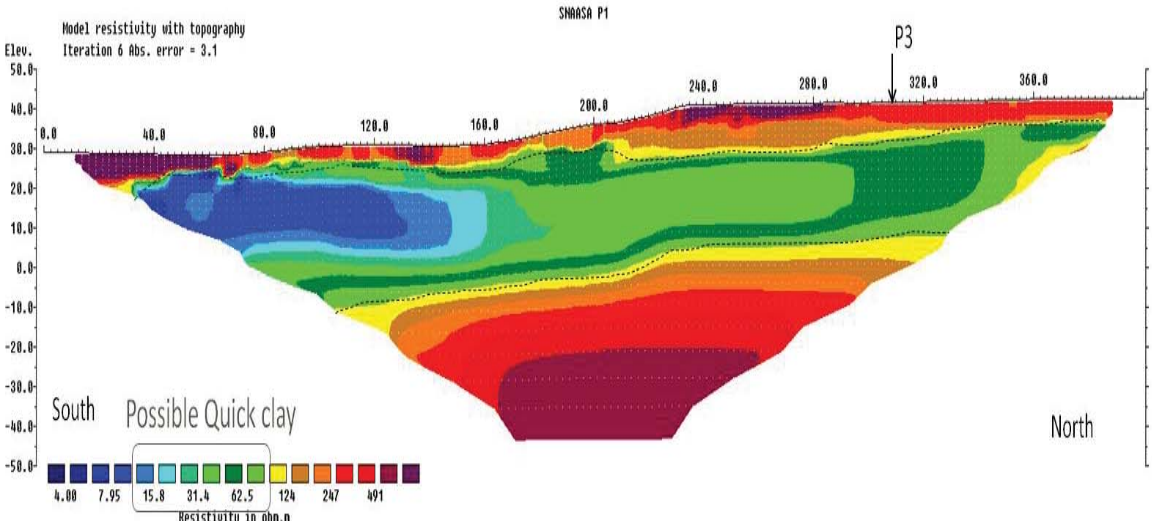


Figure 3.11: Resistivity model along a slope in Snåsa. A boring at ca. profile 300 indicates quick clay, and the ERT-model indicates that the clay layer is less leached further down the slope. (NGI report 20110935-03-R).

(b) In addition to this geological uncertainty come the limitations in resolution. The resolution in ERT-measurements cannot be compared to the resolution of seismic, based on acoustic sound waves, or ground penetrating radar utilizing electromagnetic radiation. ERT is an integrating method and tomograms generally show a continuous transition from low to high resistivity and vice versa. This means that a thin clay layer above the rock surface with high resistance will be interpreted with too high resistivity, which can be misinterpreted as leached clay. It is also challenging to plot correctly the transition from clay to rock. Constrained inversion can improve the results considerably, see Figure 3.12.

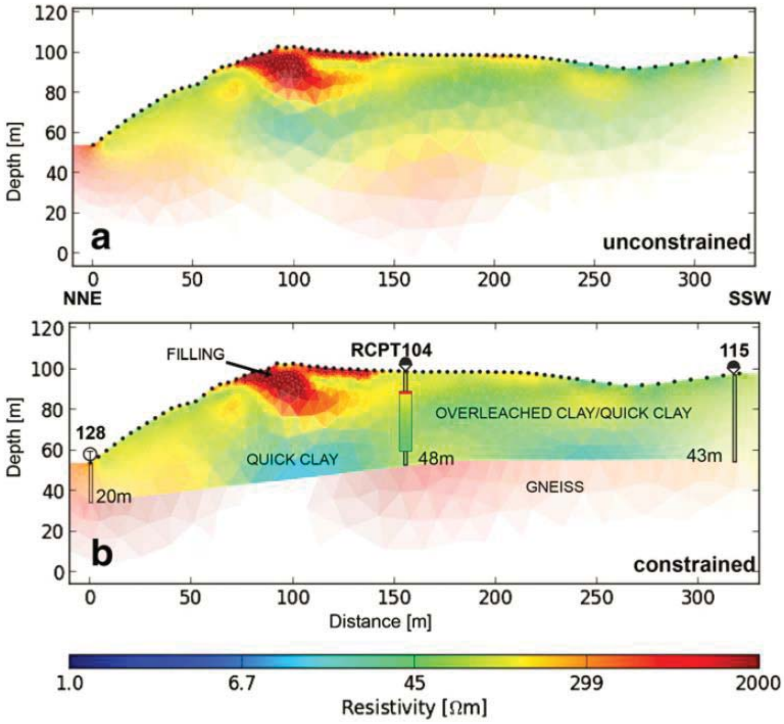


Figure 3.12: Two resistivity models corresponding to the same data set, but also two different data processing methods.

(a) Unconstrained inversion with no given boundaries in the profile.

(b) Constrained inversion where the results from 3 existing soundings are used to assess the depth to bedrock. The resistivity measured by R-CPTU is drawn in the same colour scheme.

Using constrained inversion, one consider other available information in the processing of the resistivity profile, for example the depth to bedrock from total sounding or measured resistivity from R-CPTU.

Even if these two limitations are valid for the method in general, it is particularly relevant for mapping of brittle materials due to the small differences in resistivity between salt and leached clays.

It is also important to be aware that the interpretation of ERT data probably somewhat overestimates the amount of leached material.

Table 3.8 Summary – detection of brittle materials from resistivity measurements at the surface (ERT).

Detection principles	Positive features	Negative features
Resistivity values indicate the extent of leached clay. Empirical correlations between salt content and resistivity indicate leached material. Continuity of zones and layers with equal resistivity.	Results from the ERT-model can be used in planning of boring program. Gives continuous information about the soil layers in the ground. Accessibility is good for investigations in forest/dense vegetation, steep slopes and similar conditions.	Uncertainty if resistivity contrasts are due to salt content or other issues. Limited resolution, uncertain resistivity in thin layers and inhomogeneous conditions (2-4 m). Possible disturbances when small distance between the quick clay layer and the rock surface occur. Signal noise from cables and other infrastructure in the ground.

3.3.3 Airborne electromagnetic measurements (AEM)

Resistivity measurements from airplanes or helicopters (Airborne Electromagnetic Measurements AEM) can be used for detection of brittle materials in more or less the same way as ERT. AEM produce models for the resistivity in a regional scale, along profiles of almost unlimited length and several hundred meters penetration depth. The use of AEM is however not necessarily the same as for ERT. Use of AEM is favourable in regional mapping at an early investigation stage in large projects or in large-scale mapping of clay deposits, see the Figures 3.13 and 3.14.

The limitation of the method is mainly the economy in the project. AEM is very cost-effective in large projects, but it is not economically feasible to mobilize the equipment for some few kilometers of measurements. As described in Chapter 2, AEM has somewhat poorer resolution than ERT, and the method cannot be used over urban areas or roads with dense traffic.

The experiences with use of AEM in detection of sensitive clays are mixed and very dependent on the chosen equipment. Previous equipment designed for use in the mining industry is not very well suited (NGU report 2012.004), whereas equipment for hydrogeological mapping has given results close to the accuracy of ERT (Anschütz et al, 2015). As long as the clay layer is thick enough, the resolution of AEM is sufficient to detect differences in the resistivities between salt and leached clays, see Figure 3.14.

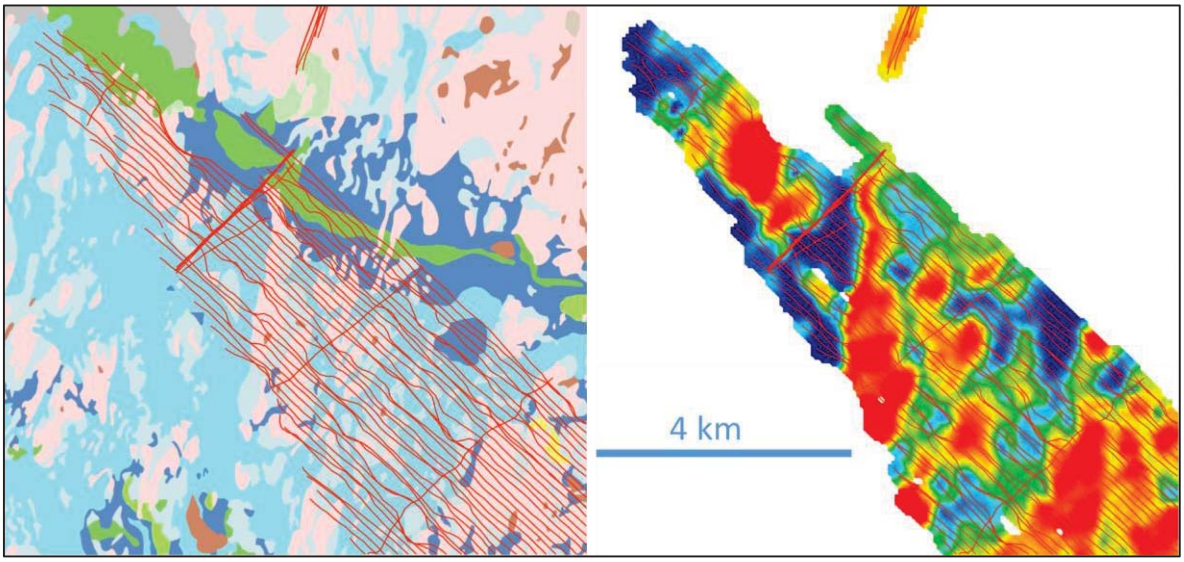


Figure 3.13: Left: Quaternary soil map (NGU) and AEM flylines. Right: AEM resistivity section from 0-15 m depth. Legend geology: Blue: marine deposits, Green: moraine, Pink: rock exposures, Brown: bog. Legend resistivity: Blue 1 Ωm to Red 1.000 Ωm. The location of the measurements is confidential.

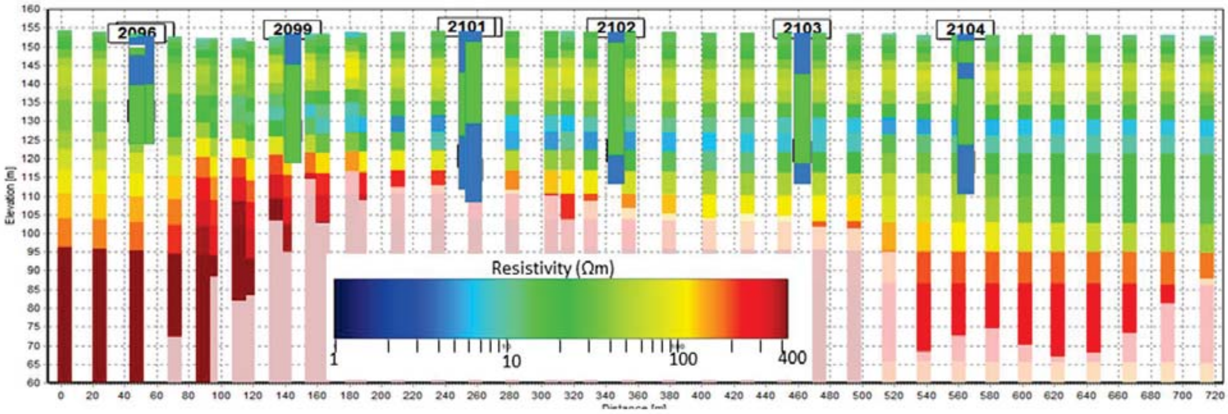


Figure 3.14: AEM resistivity model of a layer with sensitive clay close to Vorma at E16 Nybakk - Slomarka. A layer with resistivity 10 Ωm is detected and correlates to quick clay identified in borings (green).

Table 3.9 Summary – detection of brittle materials from airborne measurements (AEM).

Detection principle	Positive features	Negative features
Resistivity values indicate extent of leached clay. Empirical correlations between salt content and resistivity indicate leached material. Continuity of zones and layers with equal resistivity.	Cost-efficiency is high for mapping of large areas. Results from the AEM-model can be used in planning of geotechnical borings. Gives continuous information about the soil layers in the ground. Covers profiles of considerable lengths.	Restricted use over urban areas. The resolution is somewhat poorer compared to ERT, thin layers (5-10 m) are difficult to identify. Due to high mobilization costs the method requires projects of a certain size to be economically feasible.

3.3.4 Comparison between R-CPTU, ERT and AEM results

The difference in resolution between the three methods for resistivity measurements is important to be aware of when results from these methods are compared, see Chapters 3.3.1 to 3.3.3 for more details.

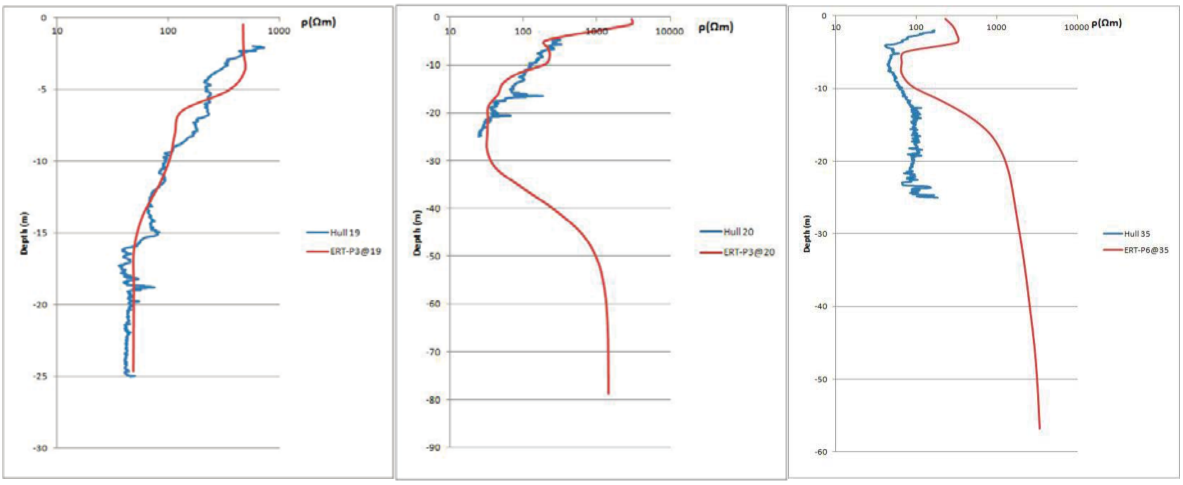


Figure 3.15: Resistivity measurements with R-CPTU (blue) compared to ERT (red) for three locations in Snåsa with very good agreement. In the figure to the right, the ERT-measurements are influenced by high resistivity in the rock beneath a thin clay layer (NGI report 20110935-03-R).

The measurements are influenced by a soil volume involving some centimeters to some tens of centimeters for R-CPTU, some meters to tens of meters for ERT and finally some tens of meter to some hundreds of meters for AEM. For example, resistivity values measured by R-CPTU for a 3 meter thick clay layer over rock with high resistivity will be correct, whereas ERT-measurements will be influenced by the rock, even in shallow measurements. AEM will probably not be able to detect the clay layer at all. The same will be the case for thin layers that are depicted sharply in an R-CPTU profile, but will show a gradual transition in presentation of ERT- and AEM-data. This is examplified in Figure 3.15.

Except from these conceptual limitations, experience show that the measurements agree well where the soil conditions are favourable.

In addition to these limitations, some material properties may cause deviations between the measurements:

(1) **Induced polarization (IP)**
When measured resistivities from R-CPTU and ERT are compared, values are measured by AC current with some kHz in R-CPTU, whereas DC current is used in ERT. It is assumed that the electric resistivity is not influenced by the current frequency. This is not always the case, and this principle can actually be utilized in measurements using induced polarization (IP). Based on existing experiences in Norway and Sweden, this effect has no significant influence on detection of leached clay, even if clay mixed in coarser materials may lead to IP effects.

(2) **Anisotropy**
If R-CPTU, ERT and AEM is used for resistivity measurements in strongly anisotropic materials, the three methods will give three different results for the electric conductivity. R-CPTU measures mainly the vertical resistivity, AEM the horizontal and ERT a combination of the two. NGI has evaluated anisotropy effects in samples of sensitive clays, but no clear influence on the electric conductivity could be found. In general, one may expect anisotropy in all types of clay.

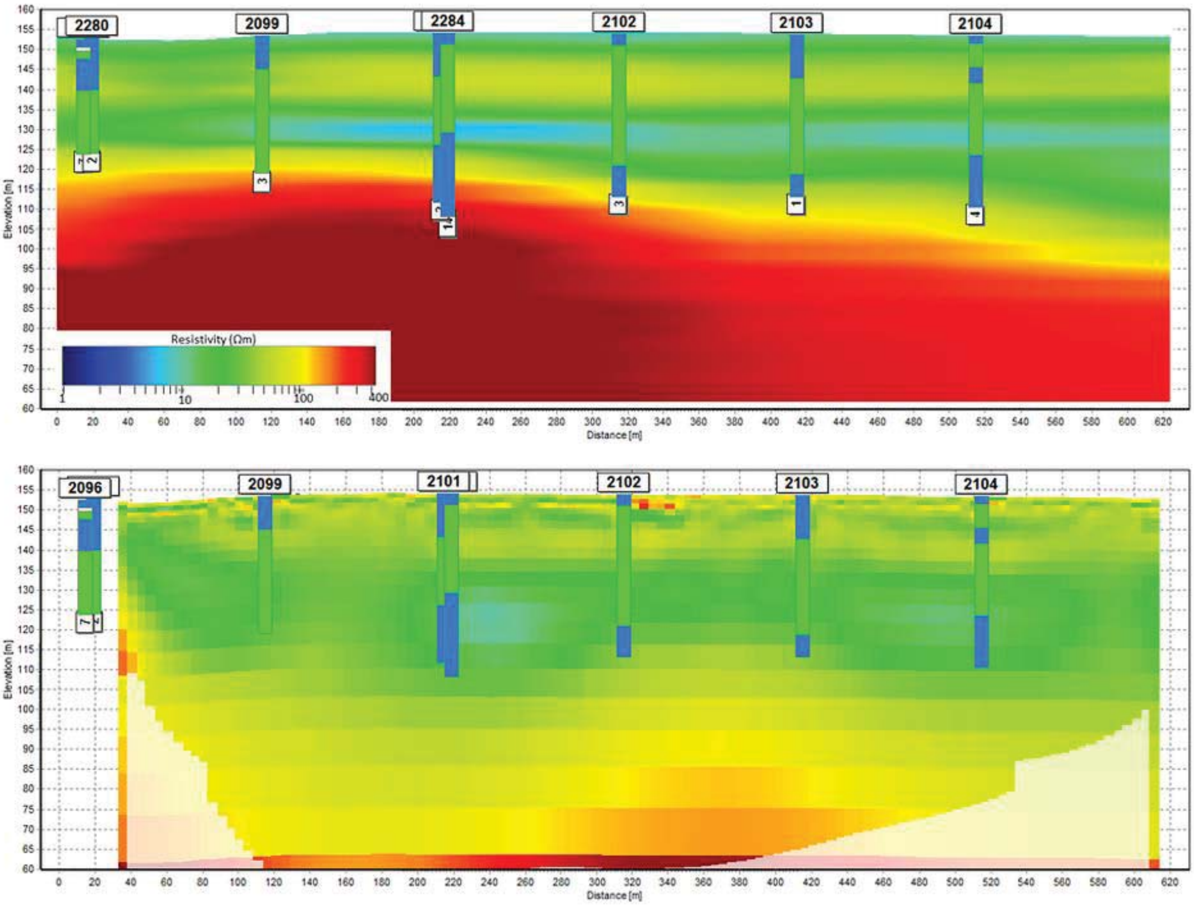


Figure 3.16: 3D and depth related resolution of AEM (upper) and ERT (lower) along a quick clay deposit at E16 Kløfta, section Nybakk – Slomarka near Vorma (Anschütz et al 2015).

(3) Sample disturbance

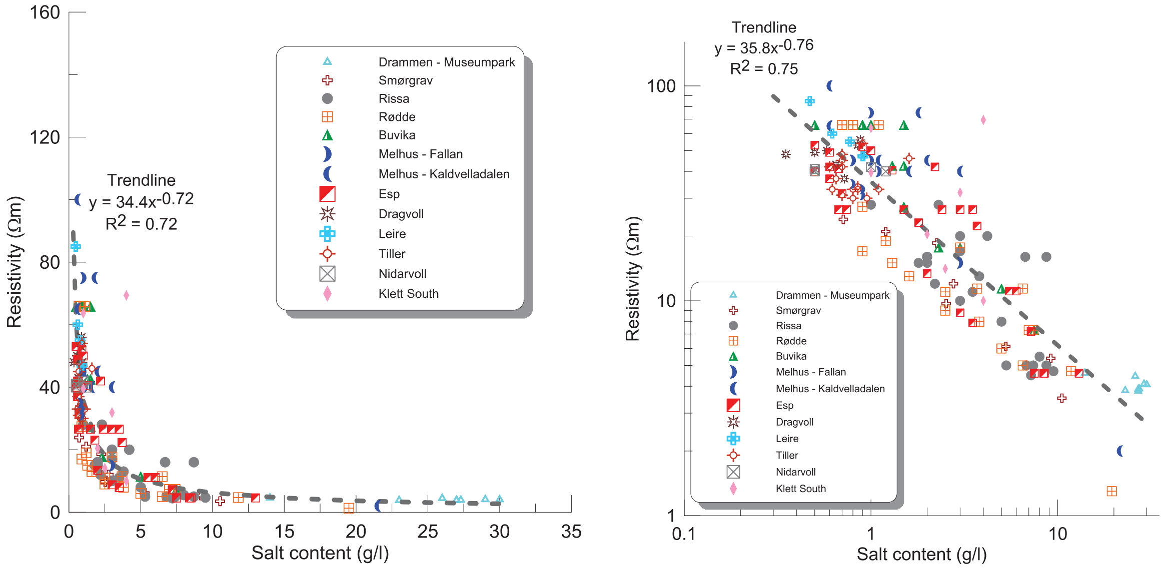
It has been speculated if the local remoulding of the clay around the R-CPTU probe may reduce the measured resistivity (Söderblom, 1958). In this study, no systematic indications of this effect have been seen.

3.3.5 Correlations between resistivity values and geotechnical index properties

While geotechnical index tests give unique possibilities for identification of brittle materials, geophysical methods are well suited to provide an overview of the ground conditions and the extension of possible sensitive layers.

It is also known that resistivity values for leached and salt clay are variables, and can vary due to site specific influence factors. The question is if unique correlations exist on a regional or national basis. In this and similar projects, a large amount of representative data have been collected, and can create a basis for correlations between resistivity and relevant index parameters. The results shown herein are based on previous work on this topic (Long et al, 2012 and Donohue et al, 2013), but more recent data have also been included. The background information for the data collection is partly shown in Enclosures A and B in this report.

The database consists of index test data from altogether 33 locations in Norway. For each of these sites, resistivity values from R-CPTU in depths where laboratory data exist have been selected. Results from ERT-measurements have also been added, if they are less than 5 meters apart from the samples.

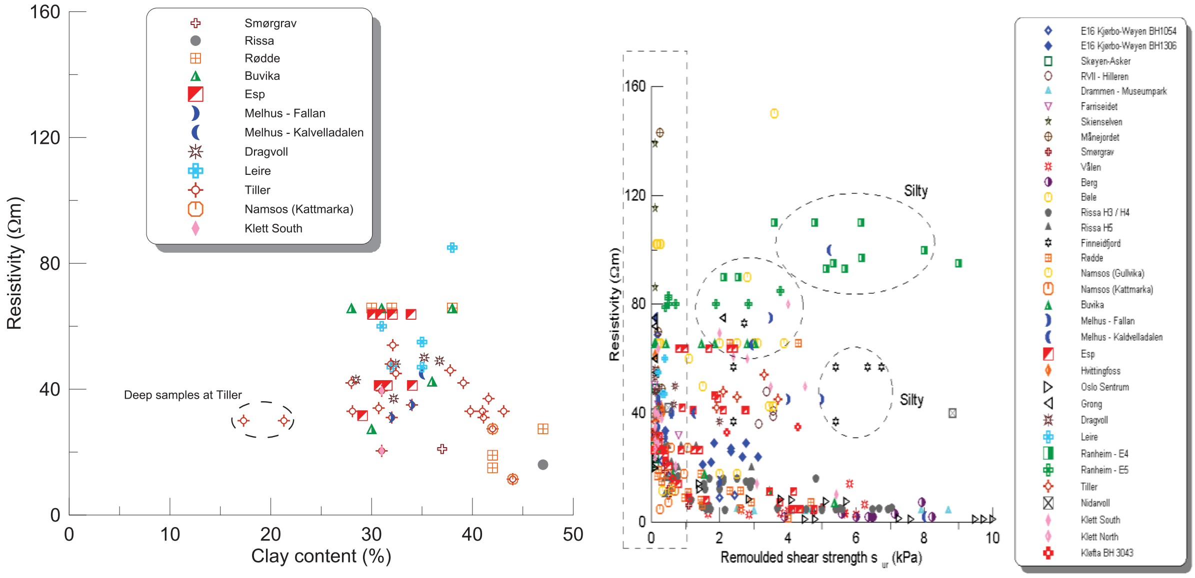


a) *b)*

Figure 3.17: Correlation between salt content and measured resistivity.

a) Arithmetic plot

b) Double-logarithmic plot



a) *b)*

Figure 3.18: a) Correlation between clay content and resistivity for samples with salinity less than 2 g/l.
b) Resistivity plotted versus remoulded shear strength.

Electrical resistivity is influenced by soil properties such as porosity, composition of the pore water, salinity and clay content. It is obvious that the salt content is the most important influence factor for the resistivity, at least for the clays included in this study, see Figure 3.17. For low salt contents (< 1 g/l), the clay content also plays an important role (see Figure 3.18 a). Since the salt content is a governing factor for the sensitivity, there also exist an indirect correlation between resistivity and remoulded shear strength. Even if this observation can be correlated, a limit value for all samples cannot be identified. The correlation also becomes poorer for an increasing number of test locations included in the statistics. In particular, silty samples show variations indicating that the resistivity is not well suited as the only classification parameter.

The resistivity is influenced by many factors, which necessarily cause some scatter in the obtained values, see the Figures 3.17 and 3.18. Whereas no global limit value or correlation exist between resistivity and index parameters, such correlations may exist for specific test sites. For the actual test site, additional information should be collected to find the soil properties that most likely causes the variations in the measured resistivity.

The resistivity values are used to indicate possible leaching of clays. A relative increase in the resistivity indicates that salt is leached from the clay, but it does not necessarily imply that the clay is quick. Time-dependent chemical weathering with exchange of ions between the grain skeleton and the pore water may stabilize the clay without a change in resistivity.

3.4 Vane testing

3.4.1 Conventional interpretation

In the interpretation of undrained shear strength, it is assumed that mobilization of shear stresses is evenly distributed at the failure surface. The undrained shear strength can then be determined from the following expression:

$$c_{uv} = 6T/7\pi D^3 \tag{3.7}$$

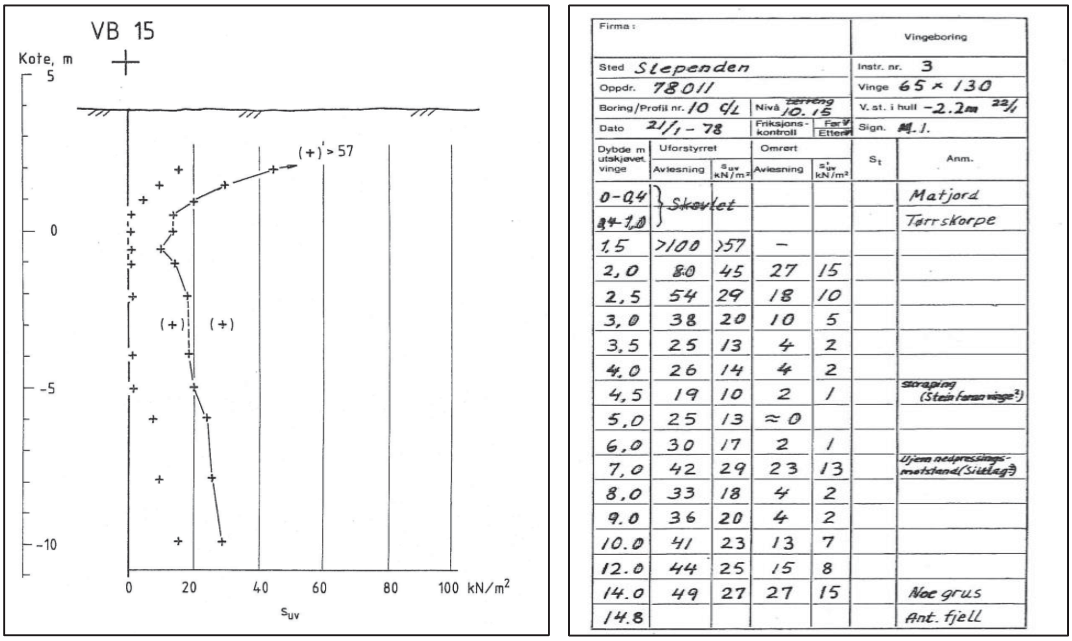
where:
T: measured torque
D: vane diameter

To determine the undisturbed undrained shear strength (c_{uv}), the maximum torque is used. For determination of the remoulded shear strength (c_{rv}), the measured residual torque after manual remoulding of the material is found. This interpretation model is conservative, and other and more correct interpretation models exist based on alternative assumptions of the shear stress distribution around the vane.

An example of presentation of test results is given in Figure 3.19.

The undrained shear strength interpreted from vane tests is influenced by several factors, such as installation effects, failure conditions around the vane, the stress situation related to development of progressive failure and the anisotropy ratio between the shear strength on horizontal and vertical planes. In a vane test, the shear strength is mainly determined on a vertical plane, which for anisotropic clays will give different values compared to similar measurements on a horizontal plane. This is partly explaining why the vane test give very low shear strength in sensitive, low-plastic clays. Furthermore, vane tests are carried out with an equivalent strain rate several times higher those applied in laboratory tests. Due to these facts, a correction factor (μ) is usually applied on the interpreted vane shear strength for use in geotechnical design, see Equation 3.8.

$$c_u = \mu \, c_{uv} \tag{3.8}$$



Firma:
Vingeboring
Sted Slependen
Instr. nr. 3
Oppdr. 78011
Vinge 65 × 130
Boring/Profil nr. 10 C/L
Nivå ~~terreng~~ 10.15
V. st. i hull -2.2m 22/1
Dato 21/1 - 78
Friksjons-kontroll Før Etter
Sign. M. I.

Dybde m utskjøvet vinge	Uforstyrret		Omrørt		S_t	Anm.
	Avlesning	s_{uv} kN/m²	Avlesning	s'_{uv} kN/m²		
0-0,4	~~Skovlet~~					Matjord
0,4-1,0						Tørrskorpe
1,5	>100	>57	–			
2,0	80	45	27	15		
2,5	54	29	18	10		
3,0	38	20	10	5		
3,5	25	13	4	2		
4,0	26	14	4	2		
4,5	19	10	2	1		Skraping (Stein foran vinge?)
5,0	25	13	≈ 0			
6,0	30	17	2	1		
7,0	42	29	23	13		Ujevn nedpressings-motstand (Siltlag?)
8,0	33	18	4	2		
9.0	36	20	4	2		
10.0	41	23	13	7		
12.0	44	25	15	8		
14.0	49	27	27	15		Noe grus
14.8						Ant. fjell

Figure 3.19 Example of field records and presentation of results from vane tests (from NGF Guideline 4).

Back-calculation of embankment failures by Bjerrum (1972) showed that design based on undrained shear strength from vane tests gave material factors $\gamma_m > 1.0$. By comparing the data, a trend showing increasing material factor for increasing plasticity could be determined. Bjerrum assumed that the two most important factors for correction of measured shear strength was anisotropy and rate effects. He separated these two effects as shown in Figure 3.20, which also shows some of the most important correction factors reported in the literature. Comparing these suggestions, Bjerrum's original correction is one of the best for Norwegian clays.

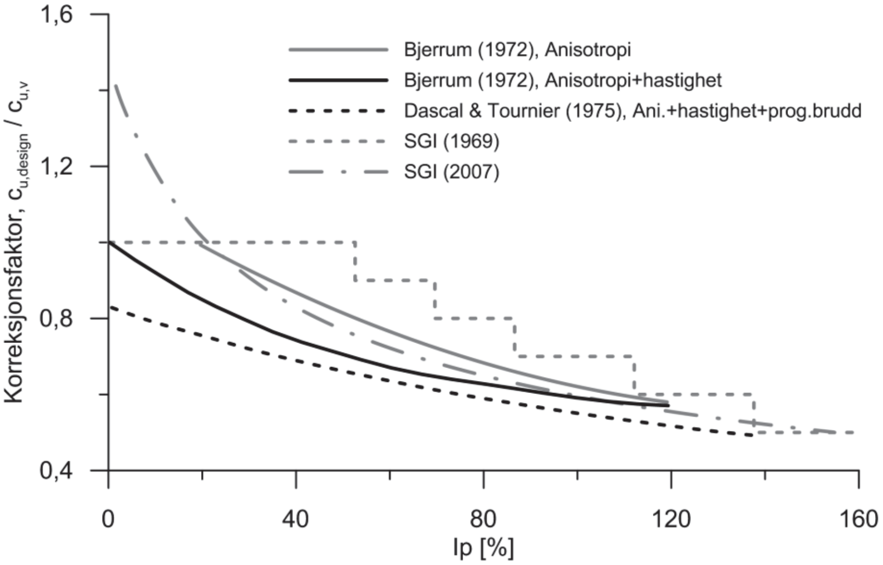


Figure 3.20 A collection of correction factors for undrained shear strength c_{uv} from vane tests.

3.4.2 Determination of remoulded shear strength from vane testing

Detection of sensitive and quick clay from vane testing is based on measurement of the torque after complete remoulding of the clay in the failure zone. This is obtained by applying 25 full rotations of the vane before measurement of the remoulded shear strength takes place. When the clay is remoulded, a local excess pore pressure is generated. Since the failure zone has a very limited thickness of about 1 mm (Gylland et al, 2013), this pore pressure will dissipate relatively quickly, resulting in an increasing shear strength with time. For correct measurement of the remoulded shear strength, it is hence important that the readings take place as soon as possible after the remoulding, to avoid excessive pore pressure drainage in the failure zone.

By using vane equipment with a slip coupling, it is recommended that the torque is measured immediately after remoulding, before reading of the resistance in the slip coupling takes place. A rotation of ca. 5^o is recommended for reading of the torque in remoulded conditions. It is further assumed that the measuring device is correctly calibrated, that the equipment is properly maintained with straight rods and an intact vane without damage. It is also important that the friction is reduced to a minimum or that it actually is measured (electric vane). The criterion for determination of quick clay is a remoulded shear strength of $c_{rv} < 0,5$ kPa.

Technically, it is challenging to measure such small torque values in the vane test. This friction is typically in the order of 1-3 Nm. The friction will increase somewhat with depth and will also depend on proper maintenance, lubrication and sufficient cleaning of the equipment. Equipment measuring the friction using a slip coupling can be utilized, but it is nevertheless challenging to distinguish what is the real contribution from the remoulded clay to the torque. Obtained results are hence influenced by considerable uncertainty.

Conventionally, the torque is applied and measured at the top of the rod system. The transfer of the applied torque down to the vane will be influenced by deformations of the rod system. Some of the applied torque will hence be lost before it reaches the vane. For a remoulded shear strength of 0,5 kPa, and a vane diameter of 65 mm, the moment contribution from the remoulded shear strength will be about 0,5 Nm. This is lower than the friction and will hence challenge the resolution of the equipment. For determination of the undisturbed undrained shear strength, the necessary resolution is suggested to be ±1 kPa. For the remoulded shear strength, a resolution about 10 times better (±0,1 kPa) will be required. This is usually not obtainable with available equipment, but electric vane systems are at least better than the manual equipment. For equipment that does not allow measurement of friction, it is not recommended to carry out measurements of the remoulded shear strength in quick and sensitive clays.

The features related to uncertainty in measurements and local consolidation result in discrepancies between remoulded shear strength from vane test and values from fall cone tests in the laboratory. Studies comparing remoulded shear strength from the vane test with corresponding values from fall cone tests have been published in a recent study in Sweden (Göta Älv investigation in soft sensitive Swedish clays, Statens offentliga utredningar, 2011). These and other studies show that vane tests may overestimate the remoulded shear strength considerably, particularly in quick clays. In this respect, one should however also recognize that interpretation of the fall cone test is empirically correlated to results from vane tests, and hence based on results database that show considerable scatter.

Figures 3.21 a-d show a summary of the remoulded shear strength measured by vane and fall cone tests in the laboratory. The data are collected from the test sites at Esp, Tiller, Klett and Fallan. Figure 3.21 (a) clearly shows that vane tests with measurement of the torque on top of the drillrods overestimate the remoulded shear strength for depths below > 10-15 m. Some few datapoints show higher recorded remoulded shear strength in the laboratory, but most of the points show the opposite. Figure 3.21 (c) indicates that the discrepancies between results from vane and fall cone tests are largest for small values of the remoulded shear strength. This is expected since the contribution from friction is relatively smaller for increasing remoulded shear strength. Effects associated with consolidation of the pore pressure may also be reduced for increasing remoulded shear strength.

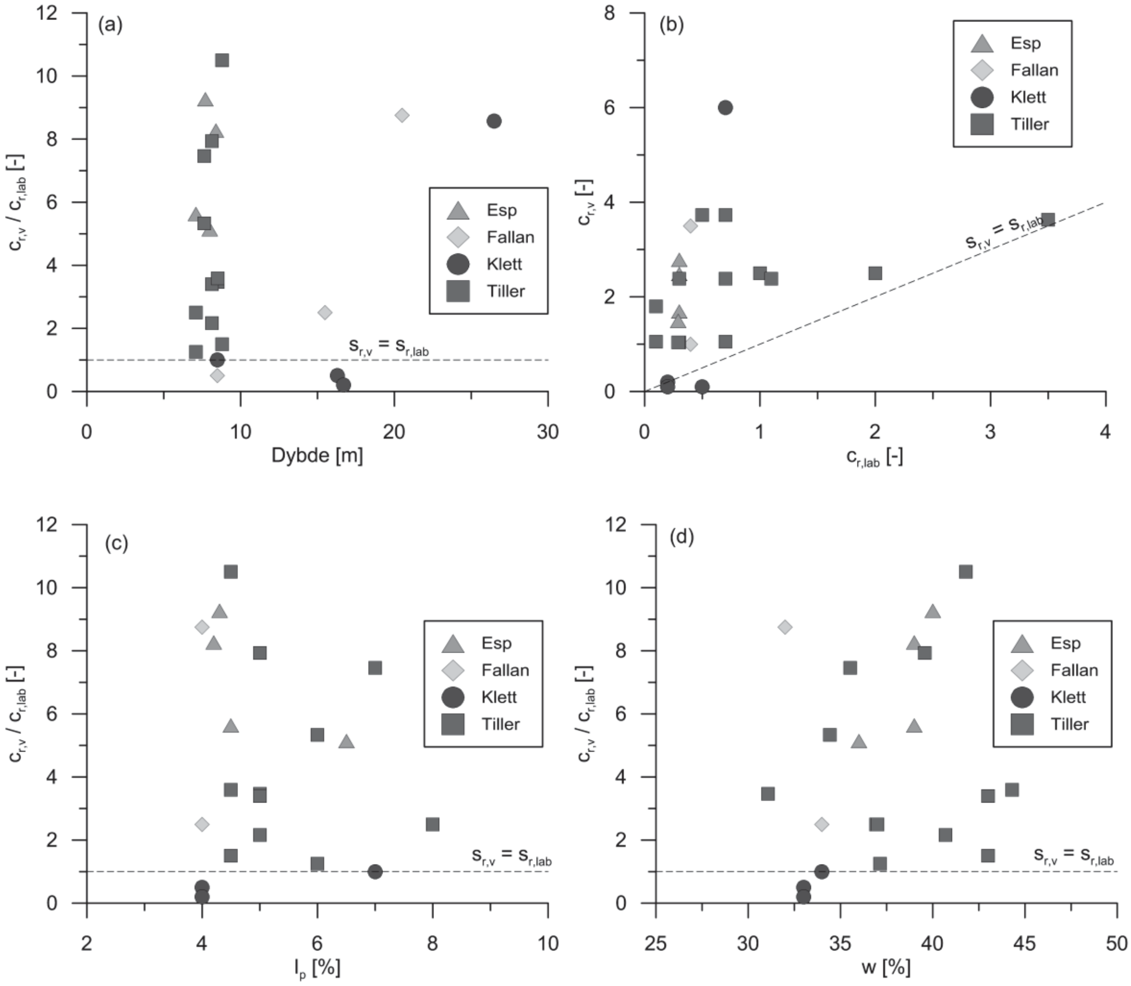


Figure 3.21a – d Comparison of sensitivity from vane tests and laboratory data (units c_u: kPa).

Remarks: (a) The relationship between remoulded shear strength from vane and fall cone tests as a function of depth. Data refer to moment measured at the top; (b) Relationship between remoulded shear strength from vane and fall cone tests as a function of effective overburden stress (depth). Data refer to the torque measured at the vane; (c) Relationship between remoulded shear strength from vane and fall cone tests; (d) Relationship between remoulded shear strength from vane and fall cone tests as a function of water content. The figure is based on data from this study and from Gylland (2015).

Some attempts have been made to find trends that can shed light on other factors, which may explain the discrepancies between results from vane and fall cone tests. No clear tendencies have however been observed, except from increasing discrepancies for increasing water content, as shown in Figure 3.21 (d). The trend is not very clear, but may be explained by the soil getting softer for an increasing water content. Consequently, the shear strength is lower with stronger influence of the pore pressure dissipation, and also larger disturbance during penetration of the vane.

Measurement of the remoulded shear strength is one of the attractive features of vane testing for detection of brittle materials. At the same time, it is evident that the method has obvious limitations in the measurement of this parameter. A large part of this limitation is due to uncertainties related to friction and other equipment effects when the torque is measured on top of the drillrods. For measurements of the remoulded shear strength in sensitive and quick clays, it is hence recommended to use vane equipment with torque measurement down at the vane. Such equipment is commercially available, and new concepts are also under development. Use and experience with such equipment will hopefully contribute to improvements in determination of the remoulded shear strength in vane tests.

3.4.3 Mobilization curve from the vane test

In an electric field vane test, the measurement of a curve showing angular rotation versus torque is carried out automatically, see Figure 3.22. The measured torque can be corrected for friction and other effects in the rod system before the shear strength is interpreted. To utilize this curve, the test must continue to minimum 90˚ rotation of the vane, so that a full failure circle is defined. Tests performed to at least 360˚ rotation show that the mobilized torque is approximately constant after 90˚ rotation.

The mobilization curve from a vane test indicates how much work that has to be done to bring the clay to failure. Soils that easily collapses will show a sudden collapse after the peak strength has been reached, whereas a more ductile material shows a more gentle reduction (see case A and B in Figure 3.23). Both of these materials will eventually reach the same residual strength at about 90˚ rotation.

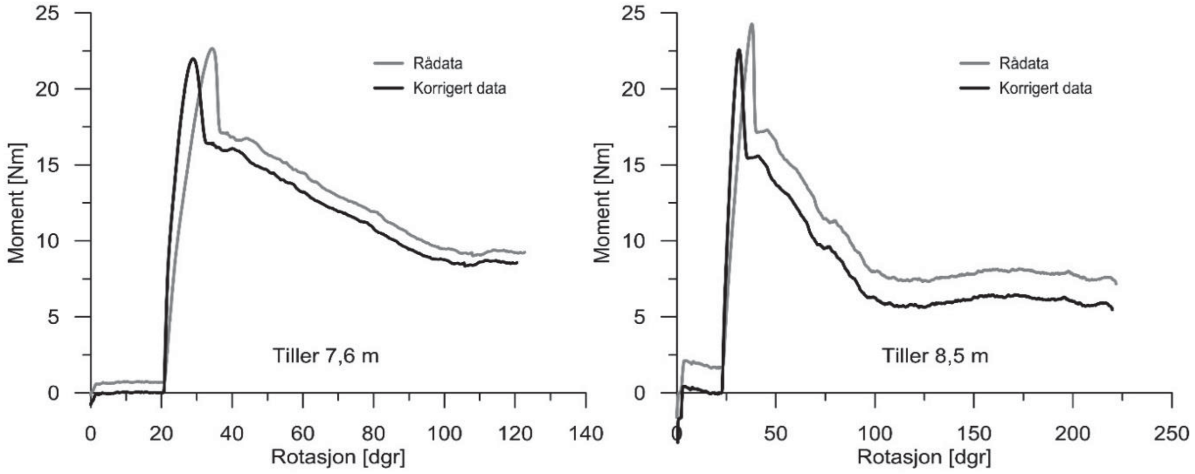


Figure 3.22 Examples of mobilization curves from vane tests, included correction for system friction.

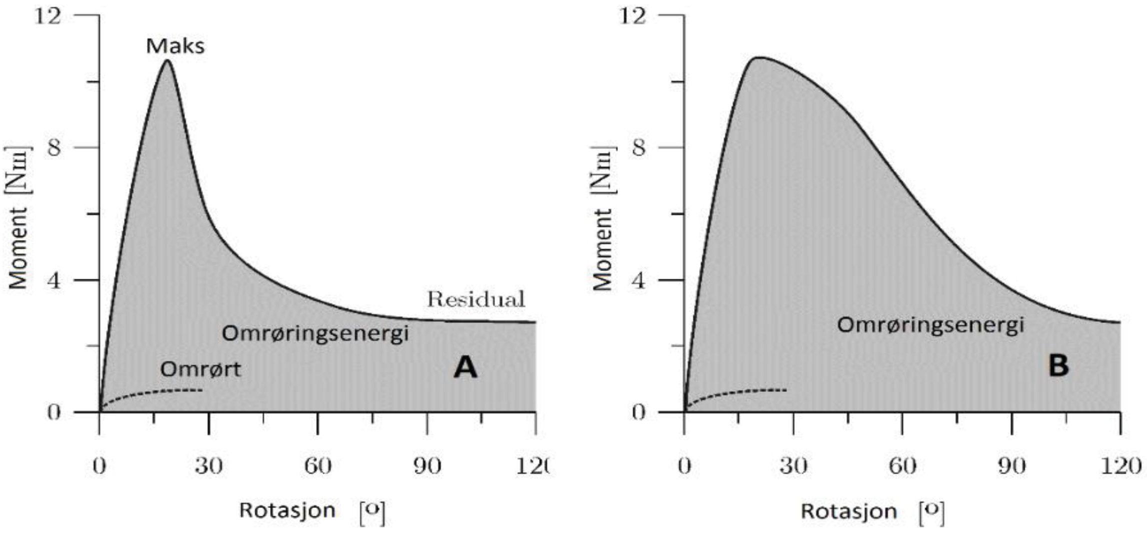


Figure 3.23 Idealized mobilization curves from vane testing. The examples A and B have the same maximum, residual and remoulded shear strength, but the necessary work to obtain these values is different.

In this context, it is emphasized that the residual strength measured at 90° rotation is not the same as the remoulded strength of the material as measured after 25 manual rotations.

An interpretation of the mobilization curve is particularly relevant in evaluation of the risk for a retrogressive quick clay slide to take place. With respect to development and extension of a such a slide, several factors may contribute. The clay needs to have a very low remoulded shear strength, and the energy released during sliding must be sufficient to remould the materials.

It is relevant to utilize the mobilization curve for the evaluation of how much work that has to be done for remoulding the clay. Several indicators are evaluated for this purpose, some of them being the remoulded shear strength, the liquidity index and sensitivity, but these parameters do not fully capture the dominating mechanism. To calculate and evaluate the necessary remoulding energy one may use a procedure corresponding to that suggested by Tavenas et al (1983) and Thakur et al (2015). The remoulding energy is calculated as the area beneath the curve for maximum shear strength versus the required degree of remoulding. This magnitude is normalized by the work that is needed to mobilize the maximum shear strength in the start of the test (W_{LS}). W_{LS} is hence the area below the mobilization curve up to failure as illustrated in Figure 3.24. One hence gets the following dimensionless expression:

$$W_N = \text{Remoulding energy} / W_{LS} \qquad (3.9)$$

For vane tests it is natural to use the remoulding energy at 90˚ rotation. To describe the degree of remoulding, the remoulding index can be used:

$$I_r(\theta) = (c_{uv} - c_v(\theta)) / (c_{uv} - c_{rv}) \qquad (3.10)$$

$c_v(\theta)$ represents the shear strength at the required degree of rotation, where I_r = 100% for full remoulding. To interpret I_r from vane tests, where the torque is approximately constant after 90˚rotation, one may use an extrapolation as shown in Figure 3.24. The stabilization of the curve at 90˚ is due to effects related to local drainage in the failure zone, and is not representative of the real remoulded shear strength.

Tavenas et al (1983) suggested that the risk for extensive retrogressive slides is largest in materials with $W_n < 40$ and $I_r > 70$. Interpretation of vane tests with data from Canadian clays is shown in Figure 3.25, where the results from this study compare well within the data trend. The figure shows that the required energy, expressed by the remoulding index I_r at 70 % of full remoulding, increases for increasing liquid limit w_l. It will require considerable work to establish a complete overview for Norwegian conditions, but this example shows how the mobilization curve and the computed remoulding energy from vane tests may be interpreted and used for evaluation of slide consequences in a mapping perspective.

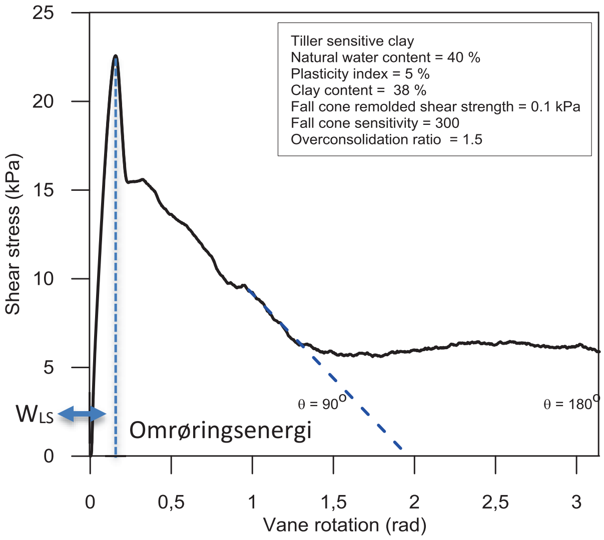


Figure 3.24 Work diagram from vane tests at Tiller (8,5 m depth). The definition of remoulding energy and W_{LS} are included. From Thakur et al (2015).

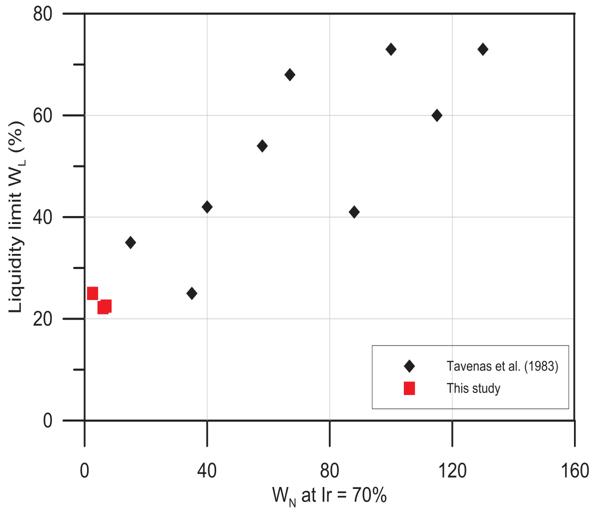


Figure 3.25 Comparison between remoulding energy from vane tests with data from Canadian clays. From Thakur et al (2015).

3.4.4 Summary

Presently, there is a renewed interest in the use of electrical field vane testing in geotechnical investigations, particularly in quick clay related problems. However, there is a need for documentation of test results, and for appropriate use of the measured data. More experience with this method has to be gained, both with respect to choice of equipment, the depth influence and principles for measurement of torque (on the surface or down at the vane). An improved procedure for performance of the vane should also be developed.

Present knowledge implies that the manual vane equipment, together with electrical field vane concepts with the torque measured at the surface, are not good enough to be used in field detection of quick clay.

Even with its drawbacks, vane testing has several strongholds that can be utilized in mapping of quick clay and related problems. With further development of equipment and procedures, the vane test can again become a regularly used test in geotechnical investigations.

A summary of recommended use of vane testing is given below:

- Undisturbed undrained shear strength
  - Plasticity $I_p > 10\%$
  - Moment measured at the surface or adjacent to the vane
- Remoulded undrained shear strength
  - $c_{ur} > 5$ kPa: Moment measured at the surface or adjacent to the vane
  - Quick clay: Moment measured adjacent to the vane
    - It is possible to obtain representative measurements with moment measured at the surface for depths less than 10 m. In this case it is very important that the equipment is clean and well lubricated to minimize the friction.
    - These findings must be verified through further research work
- Remoulding energy
  - Moment measured at the surface or adjacent to the vane
    - Must be verified through further research work

A summary of detection principles, possibilities and limitations is given in Table 3.10.

Table 3.10 Summary – detection of brittle materials from vane testing.

Detection principle	Positive features	Negative features
In situ measurement of remoulded shear strength. Estimates of remoulding energy from work curve.	Direct measurement of classification parameters without empirical interpretation models and correlations. Enable evaluation of risk for retrogressive development of quick clay slides and run-out distance through interpretation of the work curve.	Equipment where the torque is measured at the surface is not well suited for detection of quick clay. Such equipment can give too high c_{ur}-values, particularly for depths less than about 10 m depth. Performance with equipment that measures moment adjacent to the vane is recommended, and seems to give values unaffected by depth. Development of such equipment is still in the early stages. Further research and development is necessary before final conclusions can be drawn.

3.5 Laboratory measurements

3.5.1 General

Even if advances have been made in detection of brittle materials from various field investigations, laboratory test with the falling cone apparatus is still the safest method for verification of quick clay. Laboratory tests makes it possible to control the test assumptions, and the material can be observed and analyzed with respect to its properties and composition. Laboratory determination using the fall cone test on undisturbed and remoulded material should hence still be used for verification of brittle materials. However, this requires costly soil sampling in situ in a material that is difficult to sample.

3.5.2 Index tests in the laboratory

Not all index tests are equally appropriate for classification of brittle materials. Some index properties may however be used in relation to measured resistivity values, but the connections between geotechnical, physical and electrical properties in clays have not yet been fully understood. This is briefly discussed in the following:

Water content w: Gives no direct information about brittle materials. In quick clays, the natural water content w is usually larger than the liquid limit w_l.

Density ρ: Gives no concrete information about brittle materials.

Undrained shear strength c_u: Gives no concrete information about brittle materials, but the undrained shear strength is lower for quick clays under otherwise similar conditions. Sample disturbance and storage time can influence the undisturbed undrained shear strength, so that the sensitivity becomes lower.

Remoulded shear strength c_r: The definition of quick clay and brittle materials in Norway is based on the value of the remoulded shear strength ($c_r \leq 0{,}5$, $c_r \leq 2{,}0$ kPa). The determination of remoulded shear strength in fall cone tests on remoulded material is used for verification of both quick clay ($c_r < 0{,}5$ kPa) and brittle materials ($S_t > 15$, $c_r < 2{,}0$ kPa).

Note: If the samples are stored for a long time, the properties of the sampled material may change due to interaction between the sample and the cylinder. Amongst other changes, the remoulded shear strength increases with increasing storage time, which definitively will influence the quick clay determination.

Sensitivity S_t: The sensitivity of brittle materials is generally high due to the low values of the remoulded shear strength c_r. The sensitivity ($S_t = c_u/c_r$) is however not a unique measure of brittle materials since sample disturbance can influence the undrained shear strength c_u considerably. It is hence not recommended to establish correlations based on sensitivity, and the remoulded shear strength c_r should normally be preferred.

Liquid limit w_l: The geological processes that are creating quick and sensitive clays also influence some other geotechnical parameters than the strength, amongst others the liquid limit w_l. The processes that weakens the attraction between soil particles also causes lower water content in the liquid state. The value in itself is however no indicator, and the liquid limit always have to be compared with the natural water content to be able to evaluate the properties ($w/w_l > 1$; liquidity index $I_L = w - w_p/I_p > 1$). Other features than leaching may however also influence the liquid limit, for example high silt content or high organic content. In Canada, values of the liquidity index I_L are used to classify quick clay.

Plasticity limit w_p: The plasticity limit w_p gives no direct information about presence of brittle materials. It is also a difficult and time consuming parameter to determine in quick clays.

Plasticity I_P: The plasticity I_p is often very low (5-10 %) in quick clays due to the low values of the liquid limit due to leaching. However, similarly low values may be encountered in non-sensitive clays. Beyond that, the plasticity gives no direct information about the quick clay status.

Grain size distribution: The grain size distribution (clay content) gives no information about the quick clay status, but a high clay content may influence the soil resistivity.

3.5.3 Determination of salt content

The salt content in the pore water is often described as the most important factor for formation of quick behavior in marine clays. Today, it is generally accepted that pore water with a salt content less than ca. 2 g/l is a necessary requirement for quick clay behaviour. Despite that, there are examples of marine clays with very low salt content that does not show quick behaviour, probably due to weathering and ion exchange processes between the surface of the mineral grains and the remaining ions in the pore water. Tests have shown that special ions such as magnesium (Mg+) or carbonate ions (CO_3-) are represented in the pore water in such clays, see for example Løfroth et al (2011). On the other hand, there exist examples of clays with salt content higher than 2 g/l that show quick behavior.

Salt content in the pore water can be measured by several methods. Chemical analyses in the laboratory can identify dissolved electrolytes in the pore water and quantify these. Other laboratories are equipped with devices for measurement of the conductivity, and from that the salt content can be deduced by calibration. Both methods have advantages and disadvantages. Chemical analyses of the pore water are costly and time consuming, but give a complete overview of the dissolved salt ions. Conductivity measurements are much cheaper and quicker, but the salt content must then be derived from correlations with known brime solutions. The latter method is clearly prone to errors, since different electrolytes may give different contributions to the conductivity. The correlations are usually developed from artificial solutions (e.g. NaCl in water) or sea water with known salinity. The conductivity of water will also depend on the temperature in the solution.

The salt content of the porewater gives no direct classification of the quick clay status, but is nevertheless a useful property to measure for quick clay evaluations. The relation between salt content and measured resistivity is very clear above a certain limit (ca. 1 g/l), and the measurement of salt content may hence give a better background for evaluation of the resistivity measurements. Below this apparent threshold value, there seems to be no established relationship, and other influence factors such as clay content and plasticity will dominate.

3.5.4 Resistivity measurements in the laboratory

The key value of geophysical measurements in combination with classical geotechnical investigations is the continuous profiling, supplementing the extrapolation of borings to profiles and areas. In this way, one may establish correlations between geotechnical and geophysical properties. Since both surface and downhole measurements have some uncertainties and limitations (see Chapter 3.3.4), it is convenient to measure the electrical resistivity directly on the sampled material. Resistivity measurements in the laboratory can, better than in the field, indicate if the clay is anisotropic and/or polarizing, see example of results in Figure 3.26.

Since resistivity measurements does not attract a main focus in geotechnical laboratories, relatively simple equipment is usually used for this purpose, see Figure 3.27. The resistivity measurement is carried out on a sample with defined geometry, and the resistivity is calculated from the measurements and the geometrical factors. This approach however implies a considerable uncertainty in the measured values, where up to 20 % standard deviation have been reported (see NGI report 20091013-00-24-R).

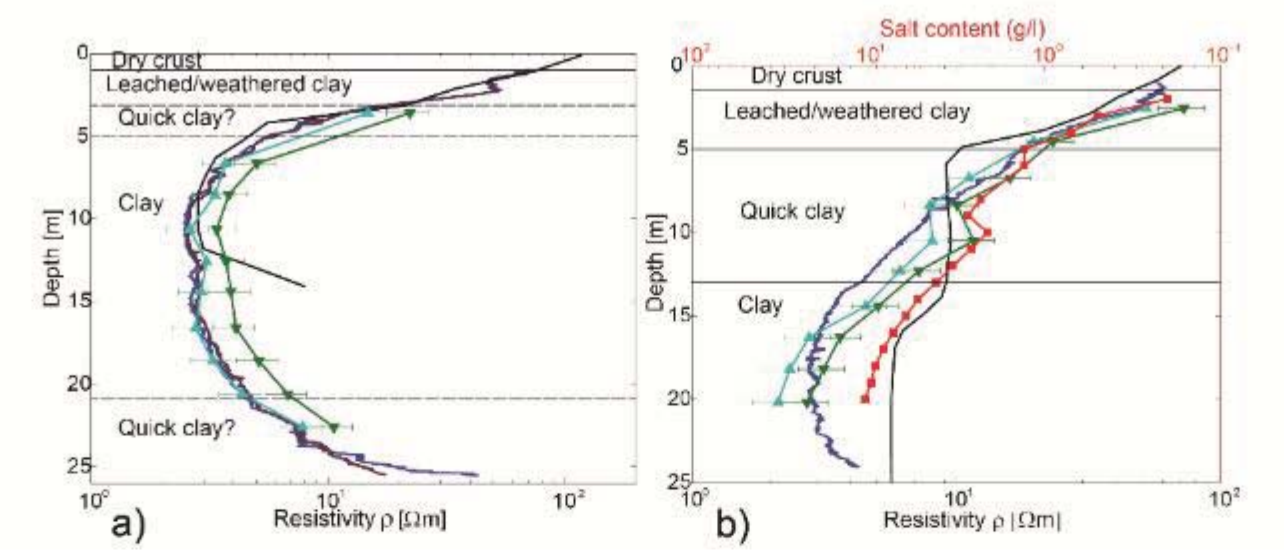


Figure 3.26 Comparison between R-CPTU results (blue and purple) versus horizontal and vertical resistivity measured in the laboratory (red, green and light blue), together with ERT data (black).

To obtain more accurate measurements and also study the dependency of current frequencies, similar equipment to that used in laboratories working with environmental testing is applied. A 4-electrode test device is normally used, corresponding to performance of ERT-measurements, to avoid electrode polarization and errors due to unknown transition resistance.

Figure 3.27 Resistivity measurements in the laboratory. Simple lay-out for measurements of electric resistivity and electric anisotropy in a sample.

3.5.5 Summary

Laboratory tests on sampled materials with use of fall cone tests on undisturbed and remoulded material is the only failsafe method for detection of quick and sensitive clays. Even if the sampled material is disturbed, the remoulded shear strength will be representative. The sensitivity will however be influenced by sample disturbance, and is hence uncertain for use in classification. For this purpose, it is also possible to carry out other relevant test on the sampled material, such as salinity measurements, mineralogy and determination of the ion content in the pore water. These are however special tests that are usually not performed in geotechnical laboratories.

Table 3.11 Summary – detection of brittle materials from laboratory tests.

Detection principle	Positive features	Negative features
Determination of remoulded shear strength in fall cone tests. Indication of quick clay when the liquid limit w_l is larger than the natural water content w. Indication of sensitive or quick clay when the salt content usually is less than < 2 g/l. Possible to measure the resistivity in the laboratory. Gives possibilities to measure the resistivity under known boundary conditions.	Safe and rapid determination of quick and sensitive clay. Determination of remoulded shear strength does not require undisturbed samples. Gives the possibilities for visual evaluation of sampled material. Gives the possibilities for full classification and identification of the material.	Requires soil samples of sufficient quality for laboratory determination of sensitivity. Difficult to obtain samples in quick and sensitive clays. Expensive and time-consuming procedures.

So far, a limited amount of resistivity measurements in the laboratory have been carried out, but this may now change. Measurement of the resistivity under controlled conditions in the laboratory seems to be necessary to understand the resistivity as a basic physical property of soils. This may in turn improve the interpretation of resistivity measurements in the field.

A summary of detection principles, possibilities and limitations for relevant laboratory tests is shown in Table 3.11.

4 Strategy for site investigations in quick clay areas

A combination of geophysical and geotechnical methods have become more usual in ground investigations nowadays, particularly in larger projects. In such integrated measurements, geotechnical engineers and geophysicists can cooperate, and by joint knowledge decide where geotechnical soundings, in situ tests and sampling can be located with optimal cost efficiency. This approach may give large advantages in terms of more cost-efficient boring locations and more confident interpretation of the results.

Resistivity measurements are well suited for mapping of possible quick clay deposits, particularly in larger projects, see Figure 4.1. With ERT measurements, one may cover corridors with possible road or railway lines in relatively short time with reasonable accuracy. As an outcome of this, one may detect critical areas of quick or sensitive clays that need further geotechnical investigations for verification. For mapping of large or long narrow linear ares, airborne measurements (AEM) can be performed to detect possible deposits of brittle material in a larger scale.

However, some limitations in the use of resistivity measurements exist, for example in areas with powered cables or other infrastructure in the ground that influence the measurements. In urbanized areas, it may hence be difficult or impossible to carry out resistivity measurements with sufficient quality. In such cases, downhole measurements using R-CPTU can be a solution, since this method is less influenced by these limitations.

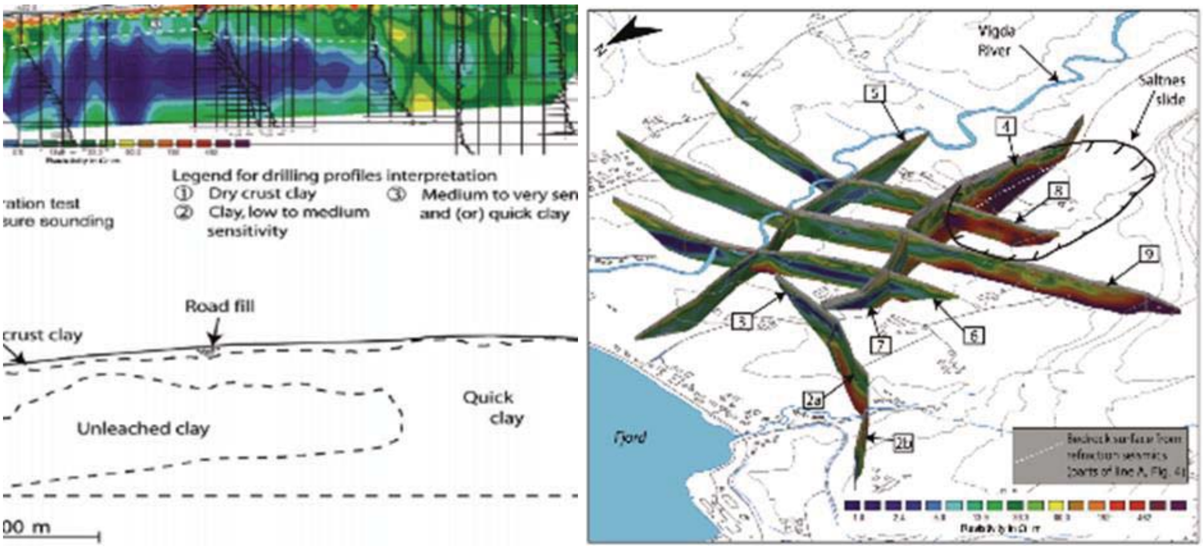


Figure 4.1 Resistivity profile with fence-diagram and results from geotechnical borings. Example of interpretation of length profile with related geological ground model. E39, Buvika, Sør-Trøndelag (Solberg et al, 2008).

Resistivity measurements may be utilized to identify barriers of non-sensitive materials in the ground, for example rock outcrops, massive layers of sand or gravel or other continuous layers of non-sensitive material. This information is of crucial importance in stability evaluations, since it enables realistic assessment of potential slide areas and run-out distances of slide debris from a possible quick clay slide.

To summarize the possibilities of combined and integrated soil investigations in larger projects, a recommended ground investigation strategy for detection of quick and sensitive clays is given in the following. Elements of this strategy can of course also be used in minor projects:

- **Resistivity should preferably be carried out in the early stages of the mapping**
  - ✓ A desk study should always be carried out in planning of a geophysical and geotechnical survey. This will help develop an optimal strategy for introductory use of ERT and geotechnical borings. AEM appears to have roughly the same potential for detection of leached clays as ERT, and is well suited for mapping of large areas and corridors in the terrain.
  - ✓ ERT is also applicable in terrain where drillrigs may have difficulties to access, also in minor projects.
- **Results from ERT/AEM can be used in planning of the geotechnical sounding program**
  - ✓ Conventional soundings are performed in a grid or along lines, based on information from ERT/AEM.
  - ✓ CPTU/R-CPTU and in situ measurements are performed at strategically important locations, based on information from ERT/AEM.
  - ✓ R-CPTU should be used at all CPTU-locations, if the equipment is available. The method requires marginal extra time compared to an ordinary CPTU.
  - ✓ Performance of R-CPTU can give more comprehensive information of quick clay status, even if the resistivity alone is not sufficient for safe detection.
  - ✓ R-CPTU may also be used to improve the processing of ERT- and AEM-results by using constrained inversion in the interpretation of resistivity data, e.g. input of known local resistivity or precise location of the layer boundaries.
- **When using CPTU/R-CPTU, the total penetration force should be recorded**
  - ✓ Recording of the total thrust enables determination of the rod friction and a friction gradient, resulting in possible identification of layers of brittle materials. This requires no additional time compared to an ordinary CPTU
- **Soil sampling should be carried out at selected locations for verification of brittle materials**
  - ✓ Localization of soil samples should preferably be based on results from ERT, soundings and CPTU/R-CPTU.
  - ✓ Fall cone tests on remoulded material in the laboratory is still the safest and most important method for verification of quick clay and brittle materials
- **The investigation program may also include in situ tests with electrical field vane**
  - ✓ The electrical field vane test may be used for interpretation and evaluation of the undisturbed undrained shear strength, the remoulded shear strength, the in situ sensitivity and a mobilization curve (NB! Note the restrictions described in Chapter 3.4.4)

Enclosure C briefly describes examples of ground investigations where a combination of introductory geophysical surveys and geotechnical borings has been carried out. Enclosure C1 describes the ground investigation program for the new E16 Kløfta, section Nybakk - Slomarka, whereas Enclosure C2 presents the evaluation of geotechnical conditions and slide risk along the Göta channel in Sweden. Both examples show how geophysical methods can usefully supplement a more traditional geotechnical investigation approach.

An overview of the various methods, showing how geophysical and geotechnical methods can be used in different project classes, is shown in the matrix in Figure 4.2. This overview can be a starting point for planning of a ground investigation, where the extent and complexity of the investigation varies from project to project. The judgement and evaluations of the consultant must be decisive for the final investigation plan, where the choice of methods is influenced by several project-specific factors, such as the type and size of the project, localization and relationships with adjacent property owners, the prevailing ground conditions, topography, the geotechnical problems involved and not least the available equipment.

Choice of project class (size of area covered) should hence be regarded as advisory. As an example, smaller road projects can be evaluated differently depending on the complexity in ground conditions and the alternative locations of the road line. In all projects where brittle materials are detected, the extent of the site investigation and the quality of test results must satisfy the requirements in NVE’s Guidelines (NVE 7/2014).

5 Summary and important conclusions

The recommended procedures presented in this report include conventional geotechnical sounding methods, CPTU, vane testing and soil sampling with laboratory tests. In addition, resistivity measurements including downhole tests (Cone penetration with resistivity measurements R-CPTU), surface measurements (Electric Resistivity Tomography ERT) and airborne measurements (Airborne Electromagnetic Measurements AEM) are included. Recommended strategies utilizing combined and integrated use of geophysical and geotechnical methods are also given, where the aim is to detect deposits of sensitive and quick deposits in a robust and cost-efficient way.

The recommendations are partly based on previously known methods or classification principles that have been further refined and elaborated in this report. However, the project also includes new approaches and methodology that can be used for detection of brittle materials. Both previously known and new methods should be used with some caution since all methods may be misleading in some cases.

The following conclusions are highlighted from the study:

- The conventional sounding methods (rotary weight, rotary pressure and total sounding) combined with sampling and laboratory test will continue to be an important methodology for detection of brittle materials. CPTU/R-CPTU and possibly the electrical field vane test will provide natural follow-up investigations in strategically important locations, where the results will be used for supplementary detection, classification and parameter determination.
- Rotary pressure sounding seems to give a more distinct interpretation of sensitive and quick clay compared to total sounding, probably due to larger sensitivity to shear resistance on the tip. Total sounding is the preferred sounding method for penetration of denser layers and for drilling into the rock surface.

	Large areas **Examples:** Large road and railway projects, larger development areas	Medium areas **Examples:** Industrial areas, schools, construction sites	Small areas **Examples:** Residential areas, local places and sites	Evaluations **Examples:** Evaluation of quick clay zones, varying number and size	General	Remarks
Background data Introductory knowledge of brittle materials can be expected	Quaternary geology Topography and location Quick clay maps Existing investigations Local relations	Quaternary geology Topography and location Quick clay maps Existing investigations Local relations	Quaternary geology Topography and location Quick clay maps Existing investigations Local relations	Quaternary geology Topography and location Quick clay maps Existing investigations Local relations	The degree of detailing can be lower for simple projects compared to more complicated cases	
Geophysics Overview of area and indication of leached clays	For large projects AEM can be relevant. Alternatively a grid of ERT-profiles may be sufficient	More than two cross and longitudinal ERT-profiles are required to cover the area	If irregular stratification is experienced, and the depth to bedrock is important, ERT should be utilized, particularly in less accessible areas	Only one to two ERT-profiles are required	Geophysical measurements are placed to cover important parts of the area. **Use:** Soil stratification and planning of geotechnical borings	Methods indicate leached clays. This is not necessarily the same as brittle materials
Simple geotechnical soundings Indication of brittle materials	Rotary pressure sounding or total sounding.	Rotary pressure sounding or total sounding.	Rotary weight sounding (when drillrigs have no access), rotary pressure sounding or total sounding	Rotary pressure sounding or total sounding	Located for optimal use and verification of geophysical data. **Use:** Soil stratification, depth to bedrock and quick clay indication	With soft, sensitive clay underlying dense and thick top layer, sensitive clay layers will not always be revealed in the sounding profile
In situ methods Indication of brittle materials, may give better interpretation than simple soundings	CPTU R-CPTU Vane test	CPTU R-CPTU Vane test	CPTU R-CPTU Vane test	CPTU R-CPTU Vane test	Located for optimal use. **Use:** Parameter-determination and soil classification	These methods give a good, but not always safe, classification of brittle materials
Sampling Failsafe detection of brittle materials	Sampling method according to purpose (classification and/or parameter determination)	Sampling method according to purpose (classification and/or parameter determination)	Focus on in situ methods, but sampling required in all projects according to Eurocodes.	Sampling method according to purpose (classification and/or parameter determination)	Parameter determination and soil classification. Required in all projects according to the Eurocodes	Focus on areas where interpretation of in situ tests is uncertain. For mapping: $0,75<B_{q1}<1,0$. For run-out: $B_{q1}>1$ in addition

Figure 4.2 Scheme with recommended use of a combination with geophysical and standard geotechnical methods.

- The penetration force for different sounding methods is influenced by several features such as soil stratification, increasing rod friction by depth, previous consolidation, effect of flushing in overlying layers etc. In particular, thick and dominating top layers with presence of stiff and coarse materials may influence the penetration force significantly. This may conceal layers of soft and brittle materials in depth. Predrilling through such layers is recommended if the circumstances allow for it.
- Interpretation of field methods may give discrepancies both on the conservative and non-conservative side, depending on the specific ground condition and the real extension of a quick clay deposit.
- Cone penetration tests with pore pressure measurements (CPTU), alternatively also with resistivity measurements (R-CPTU), have a large potential for detection of brittle materials through combined recordings of cone resistance, sleeve friction and pore pressure. When choosing these methods, one should have a more general perspective from the needs in the actual project. This perspective will usually contain project needs beyond detection of brittle materials. In this respect, CPTU/R-CPTUs enable detailed mapping of the ground conditions with determination of soil stratification, soil type and mechanical parameters.
- Use of existing soil identification charts for CPTU often gives misleading classification of brittle materials. It is recommended to use the new identification charts for quick and sensitive clays presented herein. These charts take the stress history of the materials into account, together with the pore pressures in the failure zone beneath the probe.
- Measurements of the total penetration force should always be carried out in a CPTU. This record can be used to detect layers of sensitive and quick clays by presenting the variation in rod friction with depth. The measurement does not require any additional field work, so this information comes for free.
- If CPTU is combined with downhole resistivity measurements in an R-CPTU, a new physical property is introduced in addition to cone resistance, pore pressure and friction. In this way, a wider basis for classification and interpretation of the results is obtained. The experience from this study shows that the resistivity in quick clay deposits at all test sites plots within the expected variation range 10 - 100 Ωm, most of the values being in the order of 20-50 Ωm. At some sites, non-sensitive clays were found to have resistivities between 10 and 100 Ωm, showing that variations from the common rule occur.

  This variation in resistivity values makes it less suited as a unique classification parameter. By using the ordinary CPTU data together with the resistivity, the total test records may give broader information if the clay is sensitive or not. It is hence recommended to measure the resistivity in a CPTU if a resistivity module is available, since this procedure only requires a marginal increase in testing time. Furthermore, local correlations between resistivity values and other soil properties may be established, by correlating R-CPTU results with other field and laboratory data. Such site-specific relationships may be more valuable than general correlations.
- Use of ERT- and AEM-methods gives approximately the same resistivity values as R-CPTU, and there is generally good agreement between the measured resistivities, particularly in homogenous soils. The largest advantage with these test methods is the continuous information of the soil conditions along the test profile, a feature that is very important in

evaluation of stability problems, possible slide extension and run-out distance for the remoulded and liquefied slide debris.

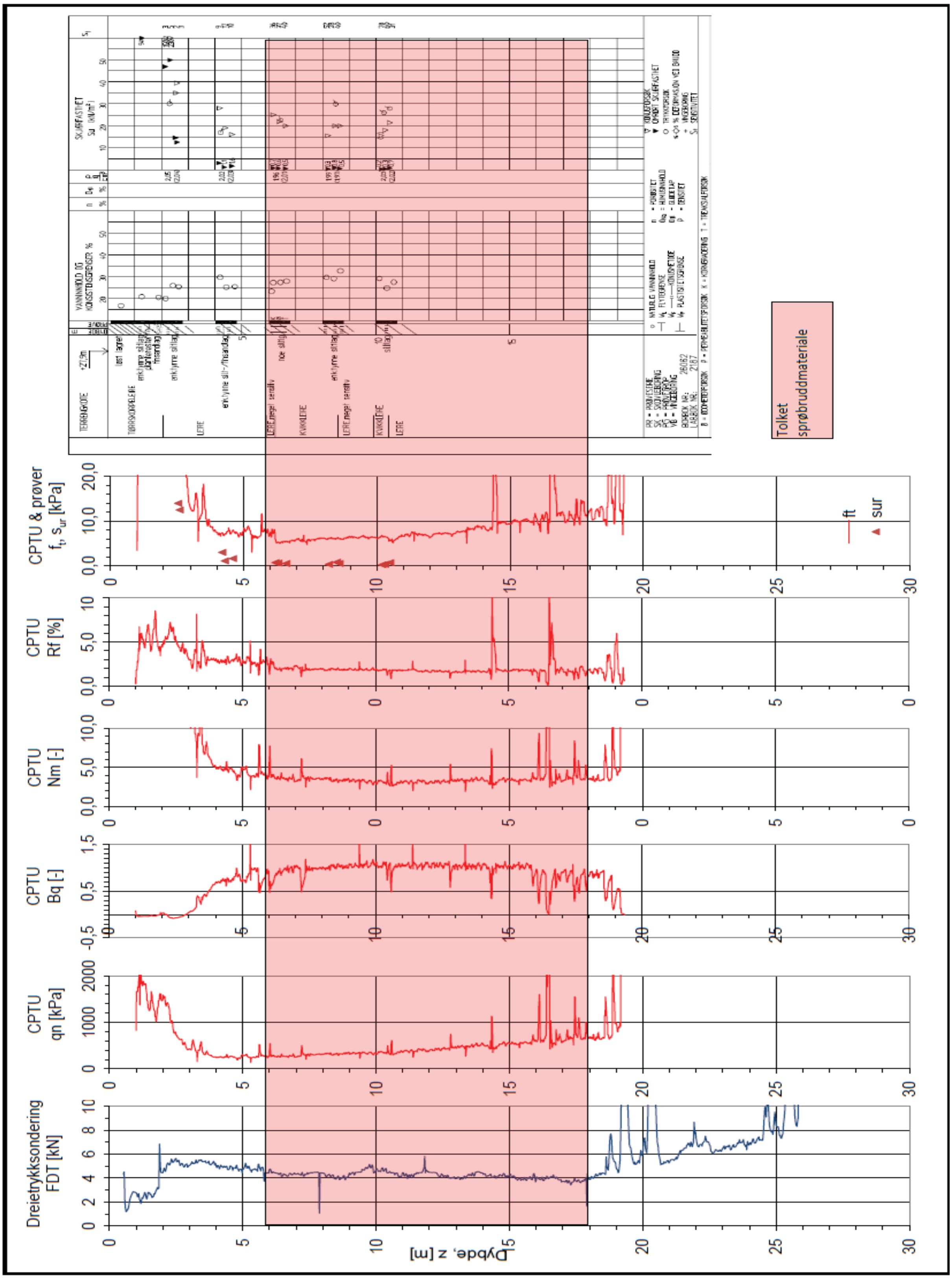


Figure 5.1 Example of summary plot of results from different test methods for evaluation of quick clay status.

- Vane tests traditionally give information about the in situ undrained shear strength (undisturbed and remoulded), and the sensitivity. The determination of the remoulded shear strength may give valid information about the presence of quick or sensitive clay, but the equipment features like friction have made the test results somewhat uncertain. Modern electrical vane systems enable measurement of the friction, using an electro-mechanical unit for application of the torque. If the torque is measured on top of the rod system, it is shown in this study that the torque measurement is heavily influenced, particularly in remoulded conditions. In this case, it is not recommended to use the method for determination of the remoulded shear strength for depths exceeding 10 m. For electric field vanes, it is required that the torque is measured down at the vane to avoid loss of torque in the rod system and consequently errors in the measurement. Such equipment is now commercially available.
- New applications in vane testing is interpretation of the mobilization curve (rotation versus torque) with respect to the required remoulding energy. This is important information for evaluation of a retrogressive development of a quick clay slide, together with an estimate of the run-out distance of liquefied slide debris.
- Determination of the remoulded shear strength by fall cone tests in the laboratory will still be the most reliable method for determination of quick or sensitive clays. This method has however also some possible sources of error, such as operator dependency and non-standard correlations between intrusion and shear strength in different countries.
- The resistivity correlates well with salt content down to concentrations around 1 g/l. For lower salt contents, other influence factors seem to dominate. This may be one of the reasons for the large scatter in measured resistivities in leached clays.
- It is recommended to summarize information from several boring methods for evaluation of presence of quick or sensitive clays, so that results from all test methods can be evaluated from the same figure. Such summary plots may always include data from conventional soundings (DT, DRT, TOT), CPTU/R-CPTU, soil sampling and laboratory tests for verification.

None of the methods reported herein are without possibility of misleading interpretation, and the evaluation of test results hence requires critical judgement and caution.

An example of summarized results from conventional sounding, CPTU and laboratory data is shown in Figure 5.1. For more examples and summary plots, reference is made to Enclosures B and C in this report. Enclosure A presents a summary of parameters from the field study.

6 Proposals for further work

This summary report presents a variety of methods for detection and mapping of brittle materials. Some of these methods have been used for a long time with mixed experiences, whereas other methods are quite new. The latter methods should have a special focus in the years to come to gain more experience with limitations and possibilities.

In particular, there is a need for further research and development in the following areas:

- The field methods described in this report do not fully separate between quick clay (c_r < 0,5 kPa) and brittle materials (c_r < 2.0 kPa, S_t > 15). The limit values used today should however be discussed more thoroughly. With respect to the classification of quick clay, it would be more appropriate to change the definitions to c_r < 1,0 kPa, meaning that the term brittle materials may be superfluous. This definition will accommodate the following features:

- The accuracy of the fall cone tests for classification of quick clay may be discussed, and the accuracy in the determination of the cone intrusion for remoulded shear strength is not accurate. The clay may as well have a remoulded shear strength of 0,4 kPa in stead of 0,6 kPa due to operator errors or bias. A change of the definition from 0,5 to 1,0 kPa will result in a more pragmatic definition of the term quick clay.
- New standardization of the fall cone tests will most certainly include a new correlation between undrained shear strength and cone intrusion. This correlation will probably have most impact on the softest materials. This will introduce discrepancies between previous and new classification. An increase of the quick clay definition may reduce this problem.
- Tests show that remoulded clays with a shear strength of 1,5 – 2,0 kPa are not liquid. The threshold value for liquid behavior seems to be closer to 1,0 kPa. A definition of 1,0 kPa will hence be in better agreement with the material properties for a liquid state. However, the potential to maintain a retrogressive/progressive failure development should also be considered, but this feature is mainly governed by energy considerations described elsewhere in this report.
- Tests on high-quality clay samples show brittle or strain-softening behaviour in most clays. The term brittle materials is hence somewhat vague, since clays generally show strain softening effects and brittle failure mode as long as the sample quality is close to undisturbed.

- Conventional soundings: Systematic organization of experiences from use of conventional sounding methods. The effect of predrilling at sites with thick top layers with coarse material over quick and sensitive clays is particularly important.
- CPTU, classification: Use of new interpretation charts based on the revised dimensionless parameters N_{mc} and B_{q1}, that in this report have been recommended for identification of sensitive materials. Experience from use of the charts in various types of brittle materials, such as fat and lean clays, organic clays and clays with different stress histories, should be gained.
- CPTU, rod friction: The measurement of total penetration force should be done routinely in all CPTUs, and used to deduce the rod friction from the CPTU measurements. The results in this and previous studies have been encouraging, but the method needs more validation in Norwegian quick clays. There are several aspects with the interpretation that requires further research, for example the use of friction reduction ring and the effect of using a large-diameter resistivity module in R-CPTU.
- Resistivity measurements, field: There is still a need for further research and development of R-CPTU, including improved interpretation procedures and the relations between resistivity and ordinary CPTU parameters. The range of resistivity values for leached clays is relatively wide, and the interpretation is also influenced by site-specific influence factors.
- Resistivity measurements, field: Comparison of results from airborne (AEM), surface (ERT) and downhole measurements (R-CPTU) of the resistivity, with respect to obtain resistivity values and possible limitations with the methods.
- Resistivity measurements, laboratory: Laboratory measurements of the resistivity under controlled conditions in the laboratory to understand which soil properties that influences the resistivity, particularly at low salt contents (< 1 g/l).
- Electrical field vane, remoulded shear strength: Use of electrical field vane tests for determination of the remoulded shear strength and detection of brittle materials. This requires measurement of the torque down at the vane, and such equipment is now available. Experiences from use of this equipment is so far promising, but the method needs further validation and systematic comparison between field and laboratory data.

- Electrical field vane, interpretation of mobilization curve: Further development of the concept for determination of necessary remoulding and release energies for quick clay slides, including evaluation of run-out potential for slide debris from such slides.
- Data processing – expert systems: Use of neural networks for data-assisted processing of criteria for brittle materials from recommended detection methods. Neural networks are mainly used in statistical analyses of data, with use of artificial intelligence (expert systems). In this context, this approach may be used for statistical evaluation and mathematical processing of the criteria set for detection of brittle materials.

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9 SYMBOLS AND TERMINOLOGY

Greek symbols

Symbol		Unit
α	Slope angle	°
α_p	Normalization ratio, undrained shear strength	-
β	Slope on shear plane with horizontal plane as reference	°
ε	Strain	%
ϕ	Friction angle	°
γ	Unit weight of soil	kN/m^3
γ'	Effective unit weight of soil	kN/m^3
γ_d	Dry unit weight of soil	kN/m^3
γ_M	Material factor	-
γ_{M0}	Initial material factor	-
ρ	Resistivity	ohm m
σ'_{ho}	In situ horizontal effective stress	kPa
σ'_{vo}	In situ vertical effective stress = p'_0	kPa
σ_{vo}	In situ vertical total stress	kPa
σ_{ho}	In situ horizontal total stress	kPa
σ_1	Major principal stress	kPa
σ'_c	Preconsolidation stress = p'_c	kPa
σ'_A	Reference stress in revised CPTU classification	kPa
τ_f	Shear stress at failure	kPa

Latin symbols

Symbol		Unit
a	Attraction	kPa
A_c	Cross-sectional area of probe (CPTU)	mm^2
B_q	Pore pressure parameter, reference pore pressure $\Delta u/(qt - \sigma_{v0}) = B_{q2}$	-
B_{q1}	Pore pressure parameter, tip pressure $\Delta u_1/(q_t - \sigma_{v0})$	-
c	Cohesion	kPa
c_u	Undrained shear strength	kPa
c_r	Remoulded shear strength	kPa
c_{rv}	Remoulded shear strength, vane test	kPa
c_{uA}, c_{uD}, c_{uP}	Undrained shear strength (A=active, D=direct, P=passive)	kPa
c_{uv}	Undrained shear strength, vane test	kPa
I_A	Activity $I_P/\%{<}2\mu m$	-
I_L	Liquid index	%
I_P	Plasticity index	%
k	Empirical correction factor, pore pressure in CPTU	-
K_0'	Effective earth pressure coefficient at rest	-
m	Stress exponent SHANSEP	-
M	Oedometer modulus	MPa
N_m	Cone resistance number = $q_n/(\sigma_{vo}' + a)$	-
N_{mc}	Cone resistance number, revised = $q_n/(\sigma_A' + a)$, σ_A' = reference stress	-
p'_0	Effective vertical overburden stress (= σ_{vo}')	kPa
p'_c	Effective vertical preconsolidation stress (= σ_c')	kPa
p_f	Probability factor	%
Q_s	Mobilized rod friction CPTU	kN
Q	Cone resistance ratio CPTU = $q_n/(\sigma_{vo}' + a)$	-
q_t	Corrected cone resistance CPTU	kPa
q_n	Net cone resistance	kPa
R_f	Friction ratio CPTU, cone resistance based = f_s*100/q_n	%

R_{fu}	Friction ratio CPTU, pore pressure based = f_s*100/Δu_1	%
S_t	Sensitivity	-
u	Pore pressure	kPa
u_o	In situ pore pressure	kPa
Δu	Change in pore pressure	kPa
Δu_2	Pore pressure change, at reference stress level CPTU	kPa
Δu_1	Pore pressure change, at tip CPTU	kPa
w_L	Atterberg's liquid limit	%
w_p	Atterberg's plasticity limit	%
z	Depth	m

Abbreviations

ADP	Active, direct and passive zones in an advanced total stress analysis
AEM	Airborne electromagnetic measurements
CAUa	Active, anisotropically consolidated, undrained triaxial test
CAUp	Passive, anisotropically consolidated, undrained triaxial test
COV	Coefficient of variability
CPTU	Cone penetration test with pore pressure measurement
DSS	Direct shear test
DRT	Rotary pressure sounding
EFVT	Electric field vane test
ERT	Electric resistivity tomography
FoU	Research and development (R&D)
FVT	Field vane test
GV	Ground water table
JBV	National Railroad Administration
NGI	Norwegian Geotechnical Institute
NIFS	Natural hazards – Infrastructure, Floodings and Slides
NTNU	Norwegian University of Science and Technology
NVE	Norwegian Water Resources and Energy Directorate
OCR	Overconsolidation ratio
R-CPTU	Cone penetration test with resistivity measurement
SVV	Norwegian Public Roads Administration
TOT	Total sounding

10 ENCLOSURES

LIST OF ENCLOSURES

Enclosure A	Detailed overview of selected test sites
Enclosure B	Summary of basic soil data from selected test sites
Enclosure C	Examples of site investigations with combined use of geophysical and geotechnical methods

ENCLOSURE A

Detailed overview of selected test sites

Eastern Norway
E16 Kløfta, section Nybakk - Slomarka
Smørgrav/Vestfossen

Central Norway
Tiller
Esp, Byneset
Klett south
Klett north
Dragvoll
Fallan
Rein, Rissa
Nidarvoll
Rødde
Ranheim west
Hommelvik seaside

Tablel A1. Summary of soil properties for selected test sites.

Test site	**w (%)**	**ρ (Mg/m³)**	**< 2 μm (%)**	**I_p (%)**	**S_t (-)**	**OCR (-)**
EASTERN NORWAY						
E16 Kløfta, section Nybakk- Slomarka	32 - 49	1.78 - 1.87	35 - 55	15 - 22	5 - 73	1.5 – 3.0
Smørgrav/Vestfossen	35 - 45	1.80 - 1.93	36 - 60	9 - 22	5 - 77	1.2 – 1.8
CENTRAL NORWAY						
Tiller	30 - 45	1.80 - 2.00	35 - 40	2 - 8	5 - 1000	2.0 – 4.0
Esp, Byneset	30 - 50	1.75 - 1.95	30 - 40	3 - 15	10-115	2.0 – 4.0
Klett south	25 - 35	1.92 - 1.94	30 - 35	4 - 10	10-240	1.5 – 3.0?
Klett north	25 - 35	1.92 - 1.94	30 - 35	5 - 10	120-350	1.5 – 3.0?
Fallan	30 - 38	1.92 - 1.96	30 - 35	5 - 10	55 - 145	1.5 – 3.0
Dragvoll	30 - 42	1.88 – 2.00	28 - 48	4 - 12	16 - 152	1.0 – 2.0
Rein, Rissa	28 - 40	1.85 – 2.00	42 - 47	7 - 12	10 - 60	2.0 – 4.0
Nidarvoll	25 – 45	1.78 – 2.04	N/A	1 – 20	5 – 200+	5.0 – 6.5
Rødde	27 – 32	1.96 – 2.01	30 – 48	5- 10	5 – 200+	1.7 – 2.4
Ranheim west	10 – 40	1.87 – 2.10	30 – 50	4 – 13	5 – 100	3.0 – 3.5
Hommelvik seaside	5 - 32	1.83 – 2.24	2 - 35	5 - 12	2 - 28	1.5 – 2.0

Table A2. Resistivity measurements – summary of information for selected test sites.

Test site	Soil type	Applied methods	References
EASTERN NORWAY			
E16 Kløfta, section Nybakk-Slomarka	Soft, quick clay	R-CPTU, ERT, AEM	Christensen, C.W. et al (2015) Anschütz, H. et al (2015) NGI report 20120491-01-R(2013)
Smørgrav/ Vestfossen	Soft, quick clay	R-CPTU, ERT	NGI report 20081135-1 (2009) NGI report 20100136-1-R (2010) Donohue et al (2009) Donohue et al (2012) Pfaffhuber et al (2010) Bazin et al (2013)
CENTRAL NORWAY			
Tiller	Soft to firm, quick clay	R-CPTU, ERT	NTNU PhD- and MSc theses: Sandven (1990) Ørbech (1999) Seierstad (2000) Long (2005) Yesuf (2008) Gylland (2011/2012) Sandene (2010) Holsdal (2012)
Esp, Byneset	Soft to firm, quick clay	R-CPTU, ERT	Thakur (2012) NTNU MSc theses: Hundal (2014) (Rambøll/MC) Torpe (2014) NGI files
Klett south	Soft, silty quick clay	R-CPTU, ERT	Multiconsult 415531-RIG-RAP-003 (2014) NIFS report R101-2015
Klett north	Soft, silty quick clay	R-CPTU, ERT	NGF seminar sampling 2014
Fallan	Soft, silty quick clay	R-CPTU, ERT	NTNU MSC thesis: Montafia (2013) NIFS report R101-2015
Dragvoll	Very soft, quick clay	R-CPTU, ERT	Multiconsult r414622-1 (2011) Multiconsult n414622-1 (2011) Multiconsult r414622-2 (2011)
Rein, Rissa	Soft, quick clay	R-CPTU, ERT	NTNU MSc thesis: Kåsin (2011) Multiconsult r414792-2 (2012)
Nidarvoll	Soft, quick clay	R-CPTU, ERT	NTNU MSc thesis: Hundal (2014) (Rambøll/MC)
Rødde	Soft to firm, silty, quick clay	R-CPTU, ERT	NGI report 20091127-00-73-R Multiconsult r413809-1
Ranheim west	Firm, silty, partly quick clay	R-CPTU, ERT	Multiconsult 416235-RIG-RAP-002 (2014)
Hommelvik seaside	Sand and firm clay and silt, non-sensitive	R-CPTU, ERT	NGI report 20130532 (2013) NGI report 20140383 (2014)

Table A3. Resistivity measurements – summary of experiences.

Test site	**Soil type**	**ERT Electrode spacing (m)**	**Maximum penetration for ERT (m)**	**Maximum depth R-CPTU (m)**	**ERT v R-CPTU**	**Remarks**
EASTERN NORWAY						
E16 Kløfta, section Nybakk-Slomarka	Soft, quick clay	5.0		40.0	Good agreement	
Smørgrav/ Vestfossen	Soft, quick clay	5.0		25.5	Good agreement	
CENTRAL NORWAY						
Tiller	Soft to firm, quick clay	2.0	25.0	16.4	Good agreement down to 10 m, ERT gives higher values beneath this level	Two parallel R-CPTU profiles show good very good agreement
Esp, Byneset	Soft to firm, quick clay	2.0 (5.0)	15.0 60.0	16.7	Good agreement. ERT is higher in the quick clay layer	
Klett south	Soft, silty quick clay	5.0	32.0	40.0	Good agreement	
Klett north	Soft, silty quick clay	5.0	57.0	30.1	Very good agreement	
Fallan	Soft, silty quick clay	5.0	57.0	31.0	Very good agreement	
Dragvoll	Very soft, quick clay	0.5	7.5	25.4	Very good agreement	
Rein, Rissa	Soft, quick clay	5.0	≈ 60.0	31.6	Very good agreement	
Nidarvoll	Soft, quick clay	5.0	50.0	27.0	ERT generally gives higher values, except in one layer	
Rødde	Soft to firm, silty, quick clay	5.0 (10.0)	60.0 (120.0)	25.7	Very good agreement	
Ranheim west	Firm, silty, partly quick clay	5.0	33.0 (B2) 20.0 (E5) 25.0 (I1)	13.7 24.0 10.2	Good agreement	
Hommelvik seaside	Sand and firm clay and silt, non-sensitive	5.0	30.0	29.2	ERT generally gives higher values	

ENCLOSURE B

Summary of basic soil data from selected test sites

ENCLOSURE B1	E16 Kløfta, section Nybakk – Slomarka
ENCLOSURE B2	Smørgrav/Vestfossen
ENCLOSURE B3	Tiller
ENCLOSURE B4	Esp, Byneset
ENCLOSURE B5	Klett south
ENCLOSURE B6	Klett north
ENCLOSURE B7	Dragvoll
ENCLOSURE B8	Fallan
ENCLOSURE B9	Rein, Rissa
ENCLOSURE B10	Nidarvoll
ENCLOSURE B11	Rødde
ENCLOSURE B12	Ranheim west
ENCLOSURE B13	Hommelvik seaside
ENCLOSURE B14	Summary plot of resistivity data from all test sites

Enclosure B1

E16 Kløfta, section Nybakk – Slomarka (Borehole BH 3043)

The work at this site has been performed as a part of the upgrading of E16 between Kløfta and Slomarka. Borehole BH 3043 has been chosen as reference location since several types of investigations were carried out at this location. The ground conditions consist of thick deposits of soft clay, with thickness up to at least 40 m. The soft clay is typical for this region, with an average water content (w), density (ρ) and plasticity (I_p) of 40%, 18,3 kN/m^3 and 18%, respectively, see Figure B1.1. The clay can be classified with medium plasticity, as opposed to the clays from Trøndelag, which are more silty and with lower plasticity.

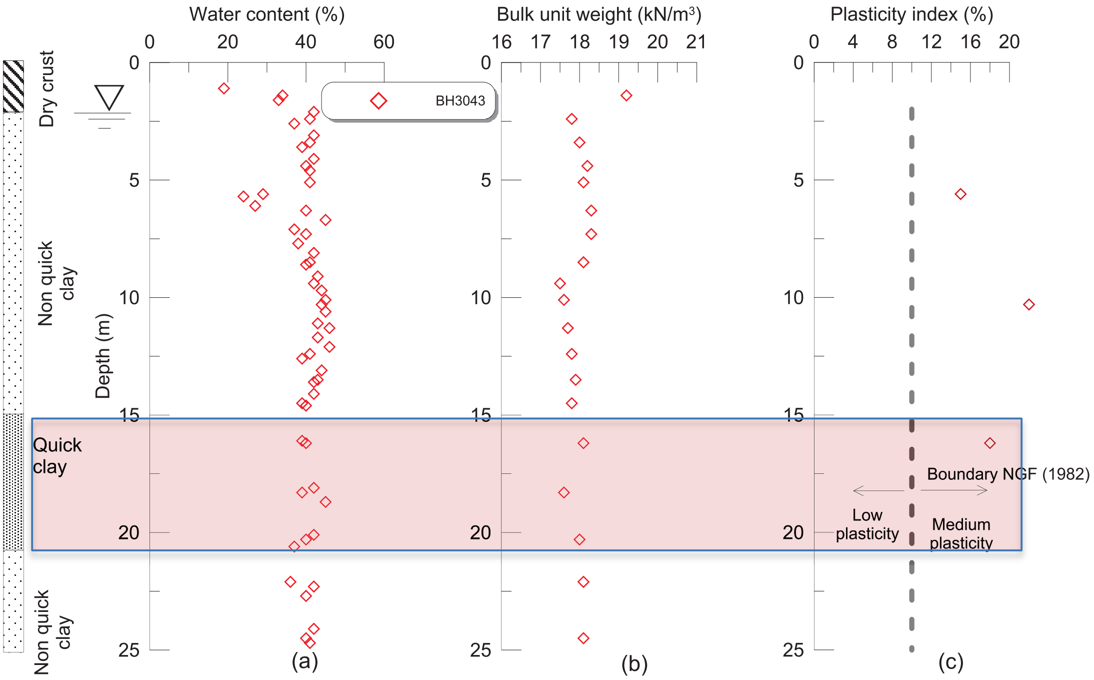


Figure B1.1. Kløfta (borehole BH3043) – basic index properties.

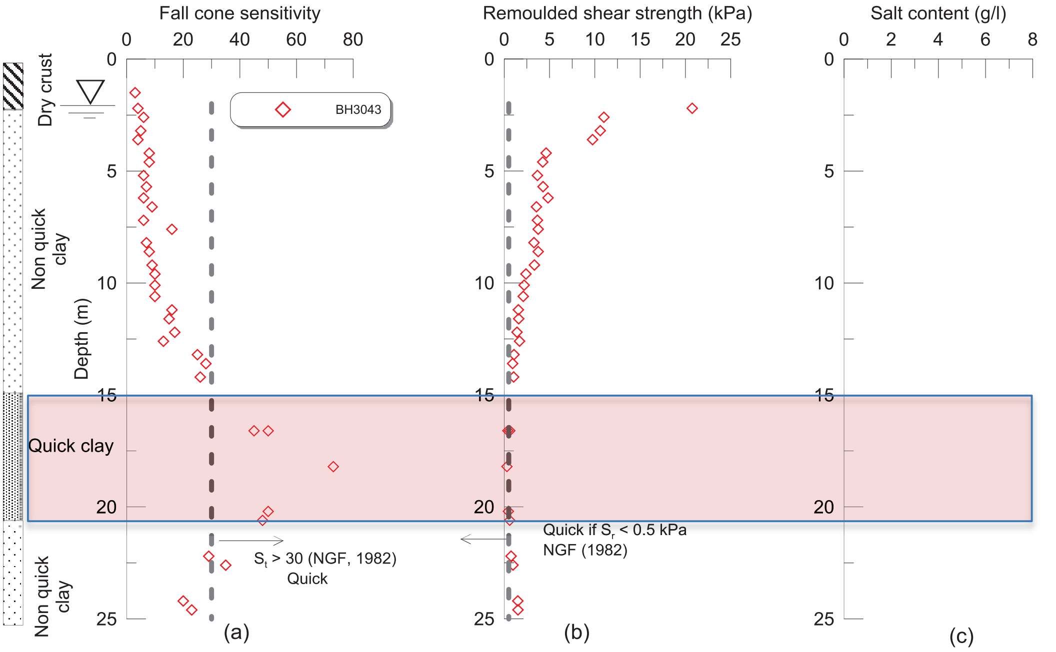


Figure B1.2. Kløfta (borehole BH 3043) – sensitivity, remoulded shear strength and salt contet.

The clay at the site is generally non-sensitive, except from a quick clay layer between ca. 15 m and 21 m, see Figure B1.2.

CPTU data from the area are characteristic for the material with corrected cone resistance (q_t) increasing from ca. 500 kPa in the top of the soft clay layer to ca. 1800 kPa at 40 m depth. The sleeve friction also shows an increase from about 5 kPa to 25 kPa in depth. The pore pressure (u_2) is generally high and far above the hydrostatic value, see Figure B1.3.

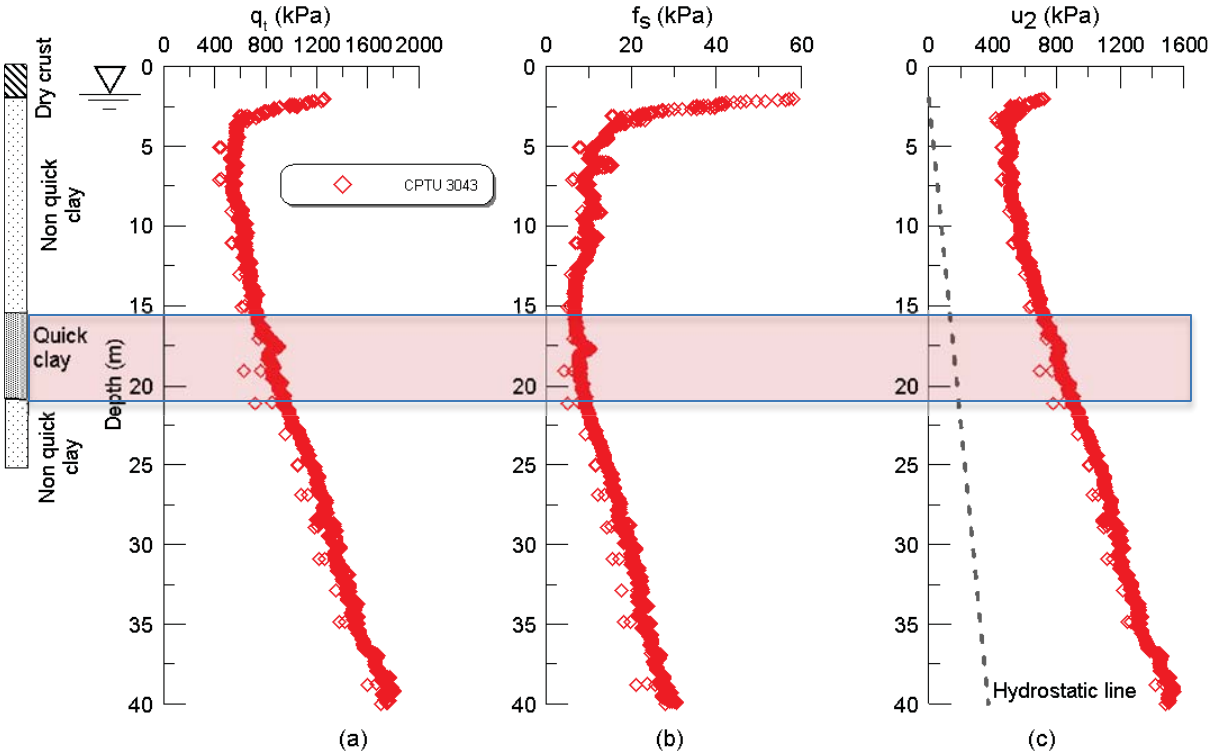


Figure B1.3. Kløfta (borehole BH 3043) – CPTU data, q_t, f_s and u_2.

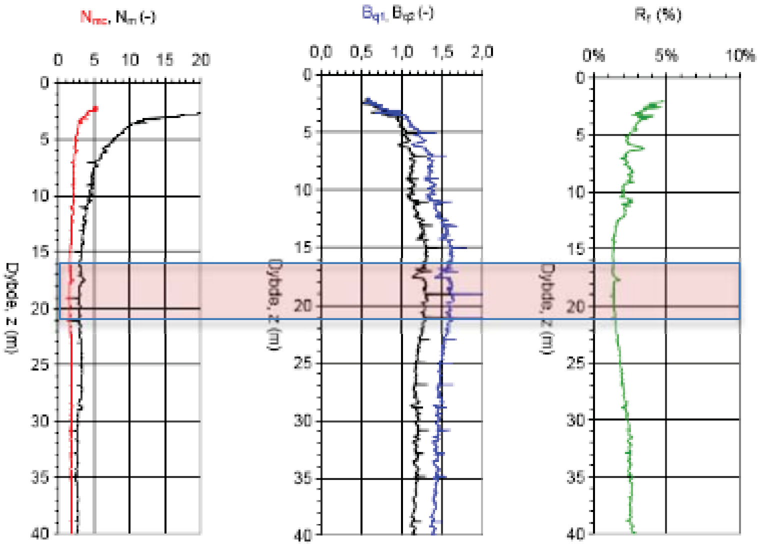


Figure B1.4. Kløfta (borehole BH 3043) – CPTU data, N_m, B_q, R_f.

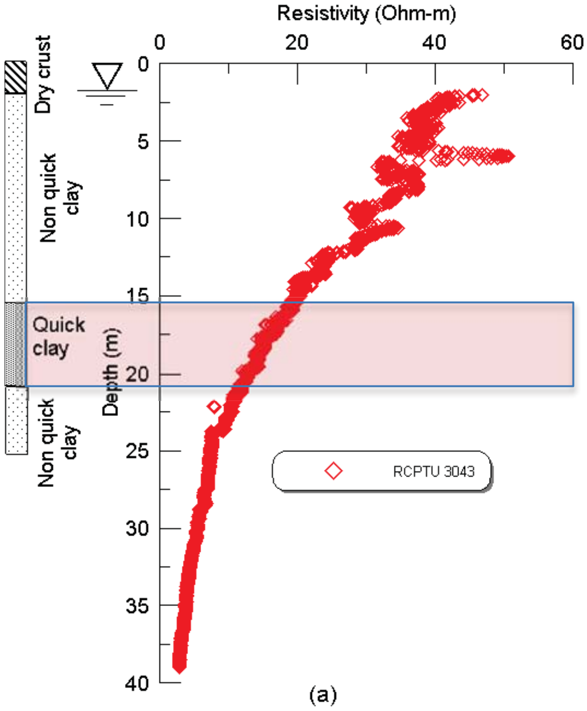


Figure B1.5. Kløfta (borehole BH 3043) – results from R-CPTU measurements.

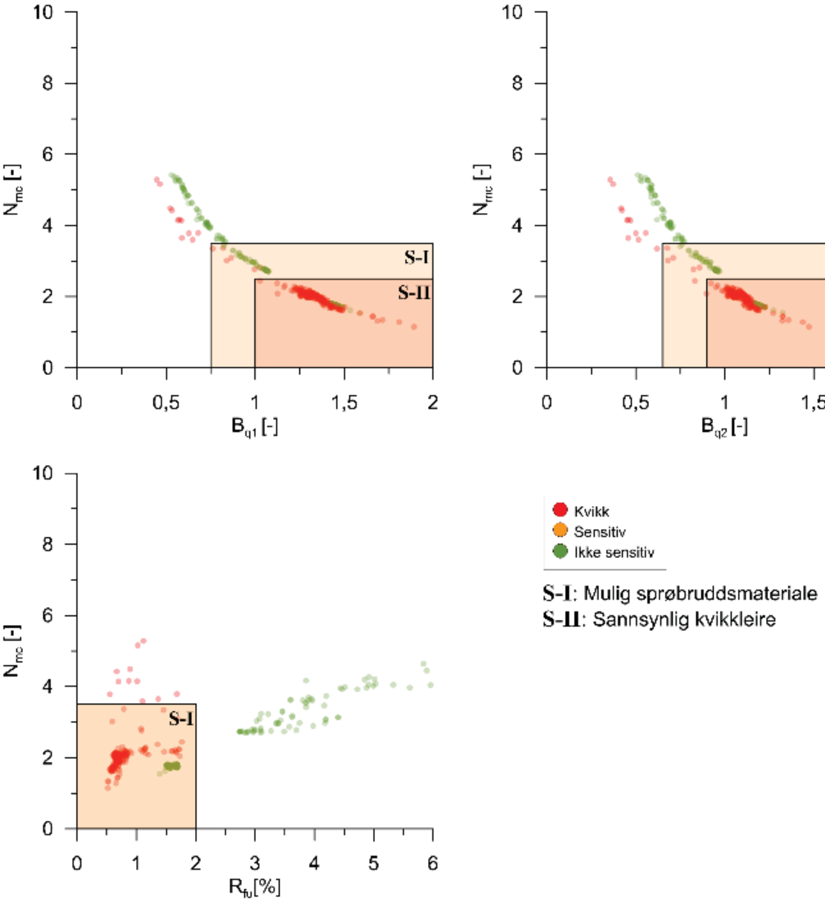
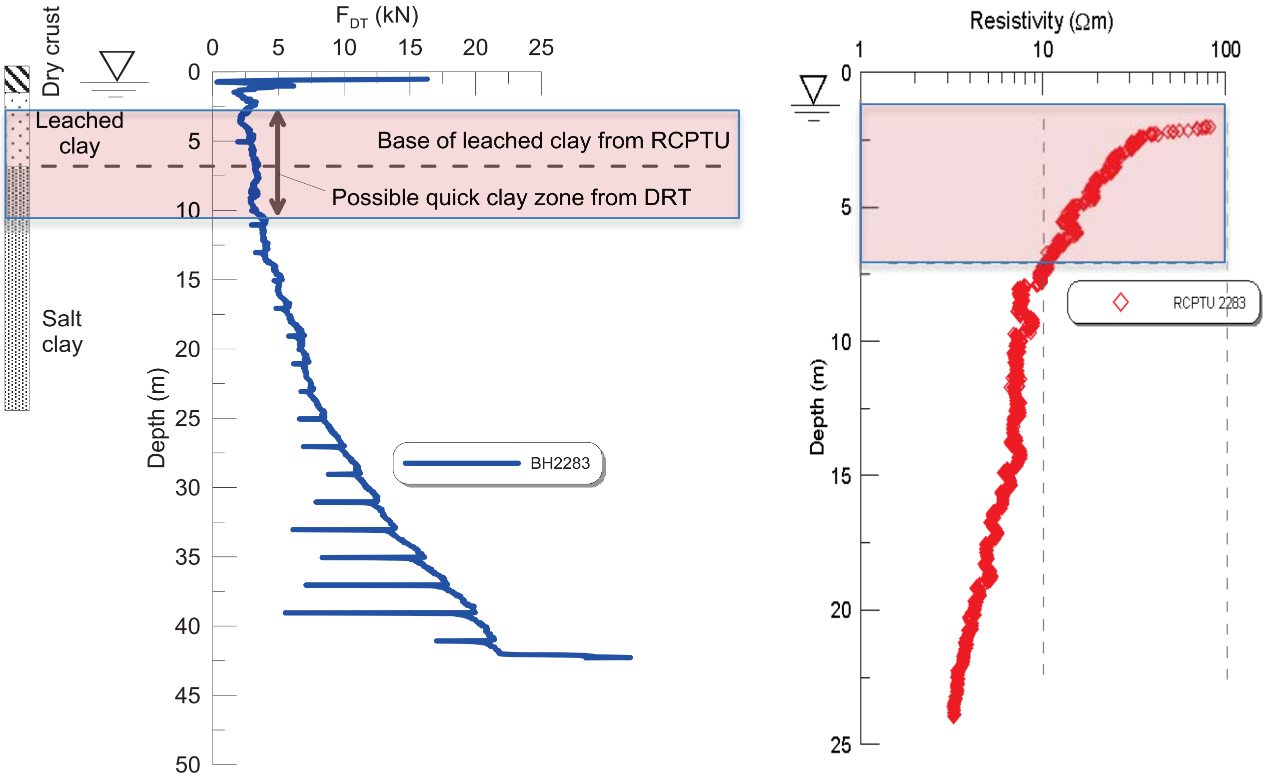


Figure B1.6. Kløfta (borehole BH 3043) – new identification chart CPTU.

The resistivity data from R-CPTU in Figure B1.5 show values that decay from ca. 40 Ωm in the top of the clay layer to very low values for increasing depths. The resistivity data does not show any distinct separation between non-sensitive and quick layers. Figure B1.7 shows a comparison between a sounding profile from DRT and a resistivity profile from R-CPTU. The resistivity values indicates a somewhat thicker layer of quick clay than what is seen in the sounding and laboratory test results.



(a) Rotary pressure sounding (DRT)

Figure B1.7. Kløfta (borehole BH2283) – comparison between sounding profile (DT) and resistivity-profile (R-CPTU). Note! Different from BH3043 in the other figures.

Important references

Publications:

1. Christensen, C. W., Pfaffhuber, A.A., Anschütz, H. and Smaavik, T.F. (2015). *Combining airborne electromagnetic and geotechnical data for automated depth to bedrock tracking*. Journal of Applied Geophysics 119, pp.178-191.
2. Anschütz, H., Bazin, S. and Pfaffhuber, A.A. (2015). *Towards Using AEM for Sensitive Clay Mapping – A Case Study from Norway*. First European AEM conference, Turin, Italy, Mo AEM 04.

Technical reports:

1. Norwegian Geotechnical Institute (2013). *E16, section Nybakk-Slomarka. Data report.* NGI report no. 20120491-01-R. Client: Statens vegvesen.

Enclosure B2

Smørgrav/Vestfossen

The test site is very well documented, and is one of the early sites that were established for testing of geophysical methods in quick clay detection. The test site is located in Vestfossen, some 1,2 km south-west of the Vålen test site. In this presentation, focus has been set on the conditions in borehole BH 505 at Smørgrav, where a distinct quick clay layer was detected in the ground. This location is also interesting since results from resistivity measurements in the laboratory are available.

Index test data from retrieved samples are shown in Figure B2.1. The soft clay at this location is quite typical for this region, with an average water content (w), density (ρ_b) and plasticity index (I_p) being 42%, 18,3 kN/m^3 and 22%, respectively. The clay is classified as medium plastic.

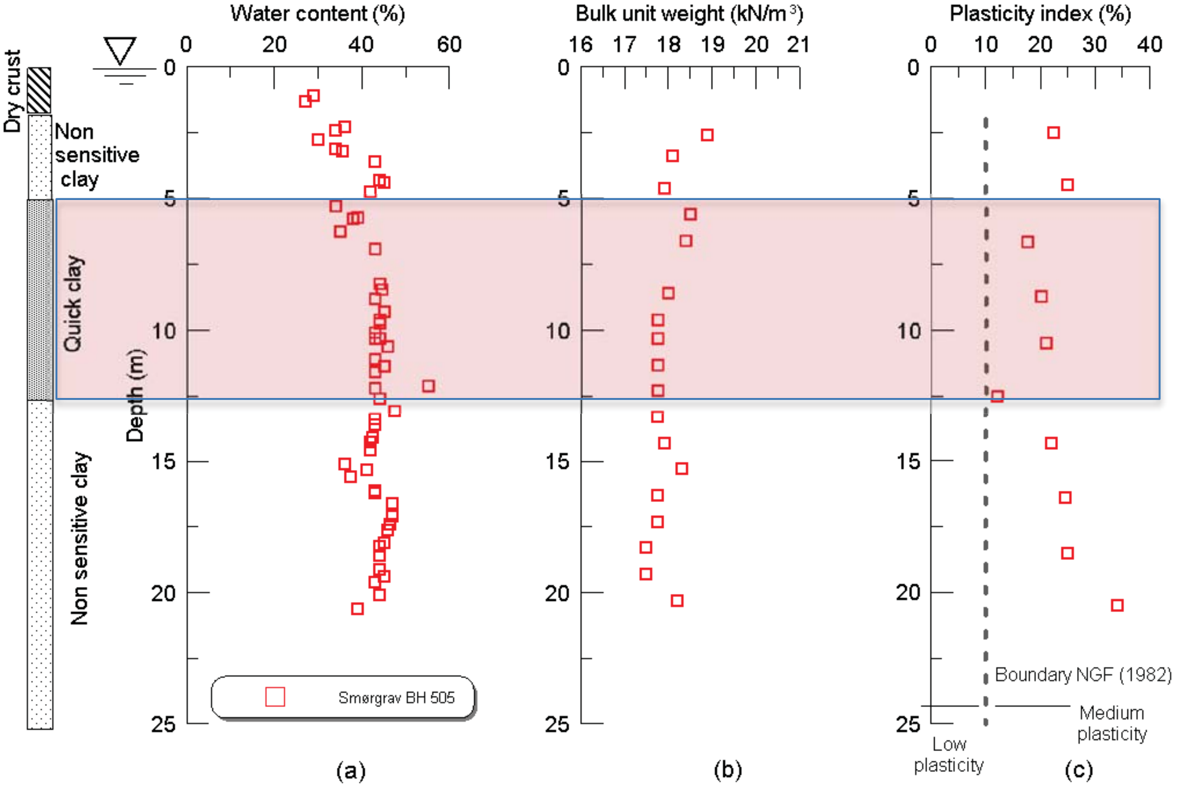


Figure B2.1. Smørgrav – basic index properties (BH 505).

Figure B2.2 shows a distinct layer of quick clay in borehole BH 505. The salt content increases approximately linearly by depth, from very low values in the start of the profile to about 10.5 g/l at 22 m depth. This shows that leaching have been taking place in the whole layer.

CPTU-data from the test site are characteristic for clays from the southern Norway, with a corrected cone resistance (q_t) increasing from ca. 400 kPa at the top of the soft clay layer to approximately 800 kPa at 20 m depth. The sleeve friction (f_s) is particularly low in the quick clay layer. The pore pressure (u_2) shows and excess component compared to the hydrostatic value in the whole profile, see Figure B2.3. Figure B2.4 shows the derived values N_m, B_q and R_f.

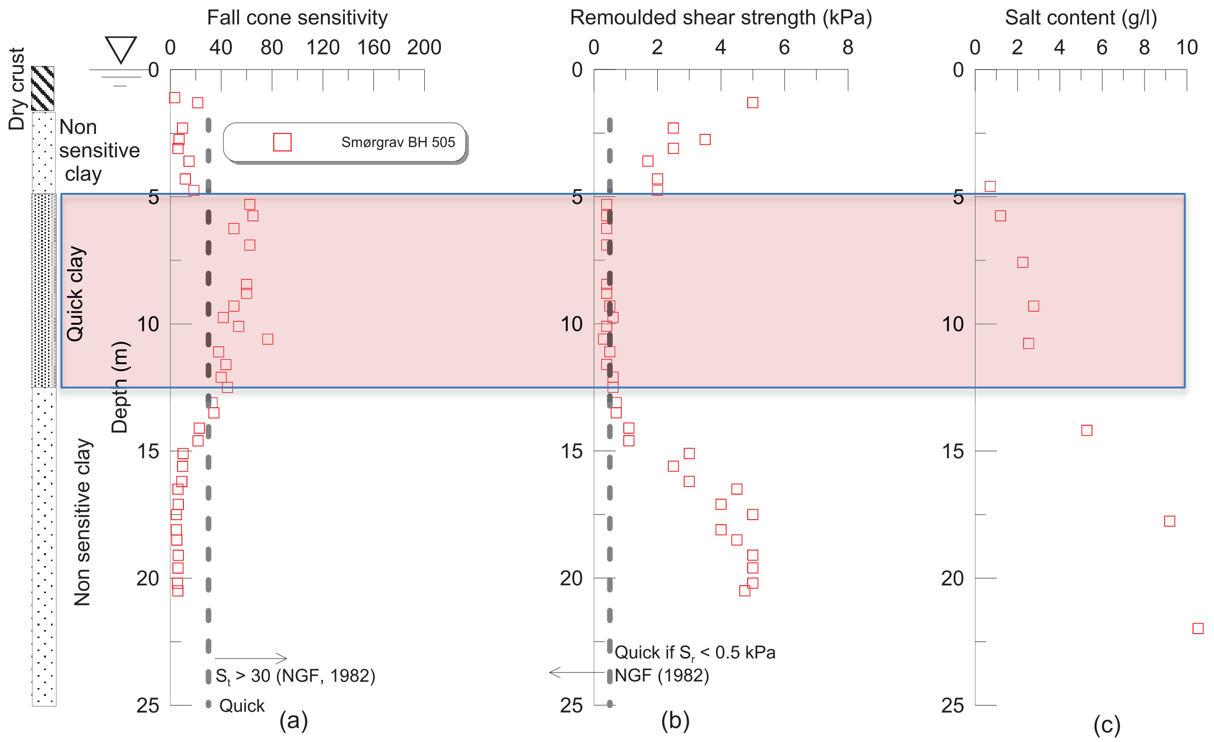


Figure B2.2. Smørgrav – sensitivity, remoulded shear strength and salt content (BH 505).

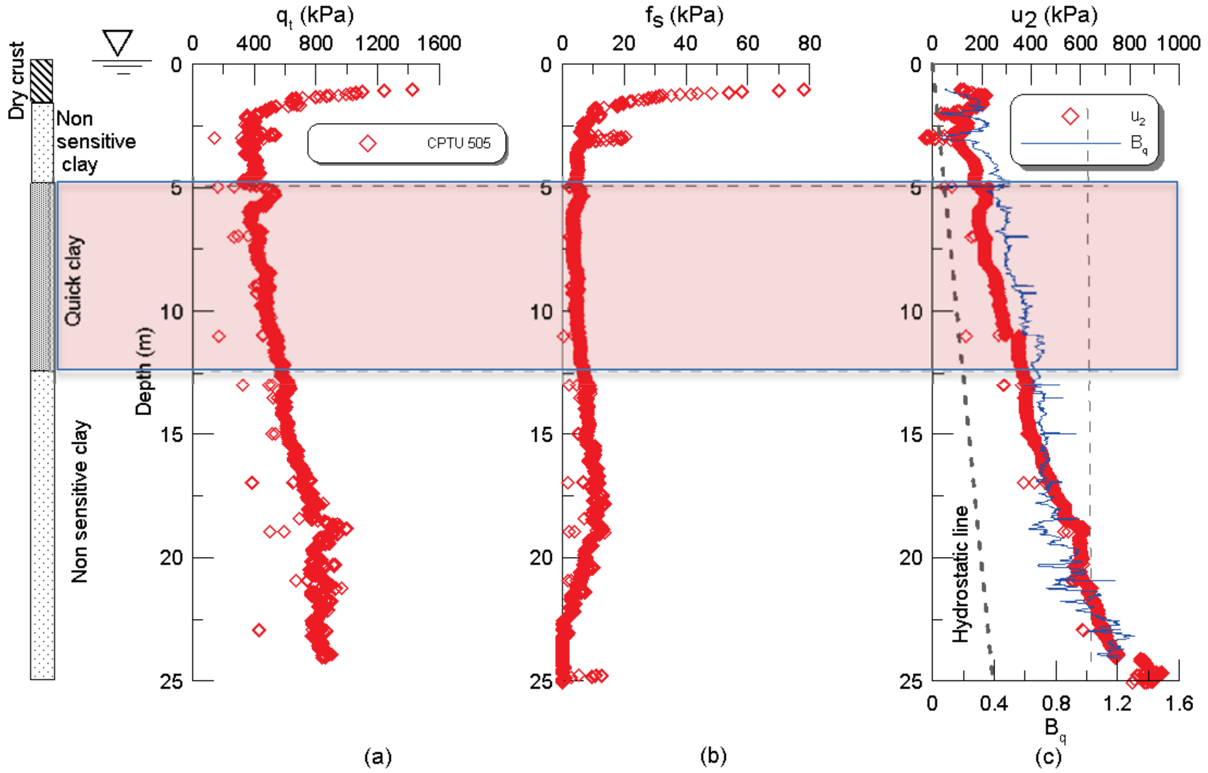


Figure B2.3. Smørgrav – CPTU data, q_t, f_s and u_2 (BH 505).

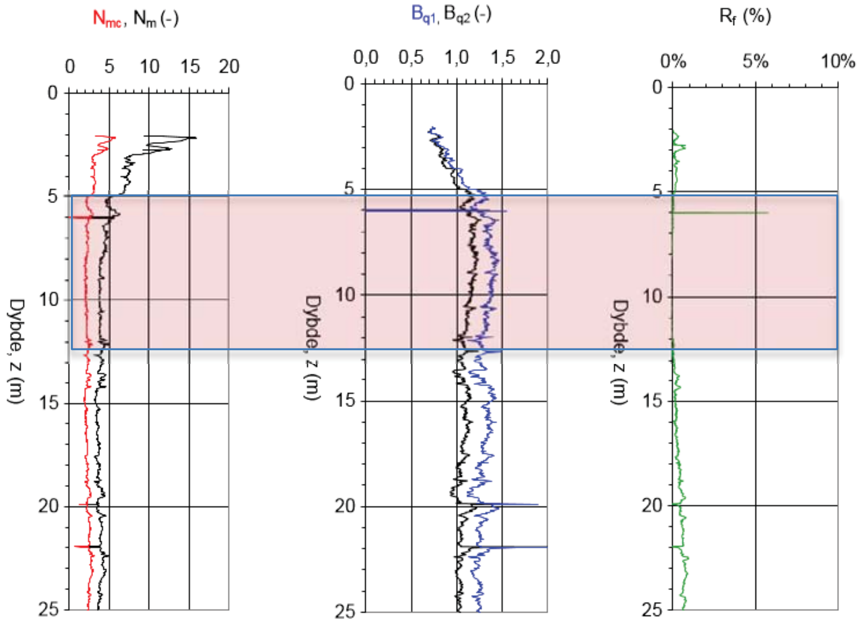


Figure B2.4. Smørgrav – CPTU data, N_m, B_q, R_f.

The resistivity from R-CPTU and laboratory tests is shown in Figure B2.5. A continuous increase of the resistivity is observed, from ca. 65 Ωm in the top of the profile to about 4 Ωm at the base of the quick clay layer. In the non-sensitive clay layer, the resistivity is approximately constant around 3 Ωm. The laboratory measured resistivities are very similar to the field values, both in values and distribution in the profile. These measurements hence confirm the measured values in R-CPTU. The laboratory measurements also shows that the resistivity values for vertical samples are about 25 % higher than the horizontal values, which indicates some anisotropy in the resistivity.

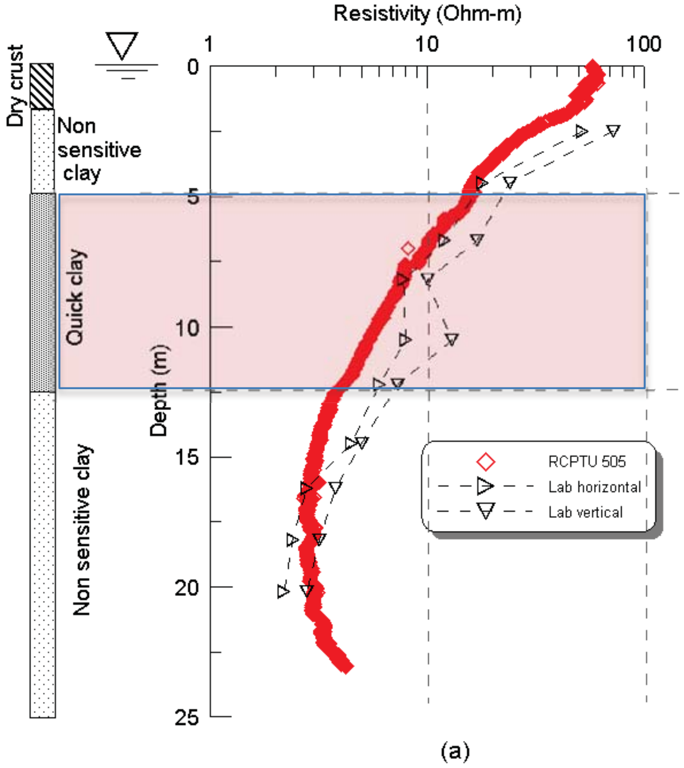


Figure B2.5. Smørgrav – comparison between resistivity from laboratory- and R-CPTU measurements.

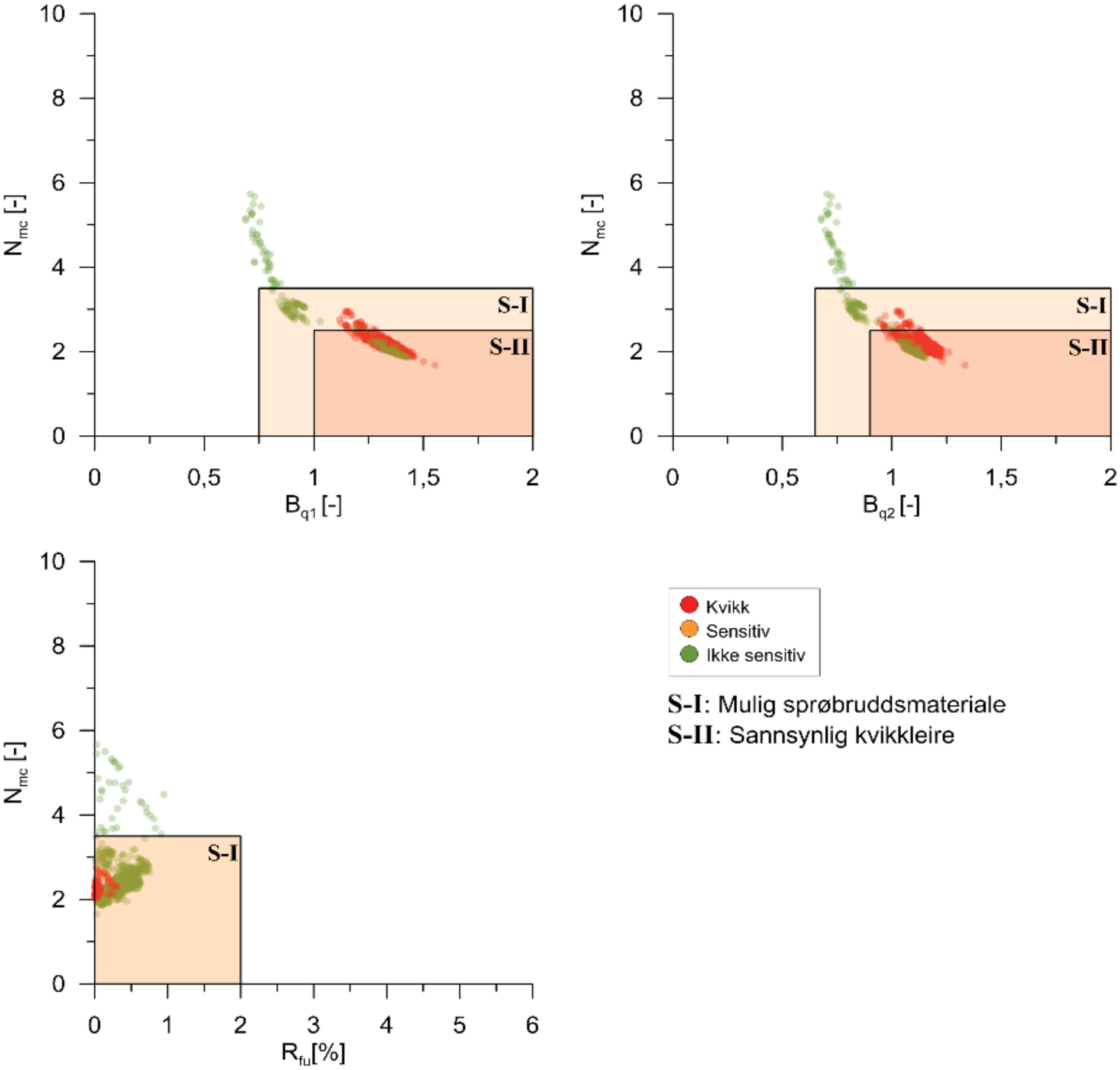


Figure B2.6. Smørgrav – new identification charts CPTU.

Important references

Publications:

1. Donohue, S. et al (2012). *Geophysical mapping of quick clay: A case study from Smørgrav, Norway*. Journal of Near Surface Geophysics, EAGE, Vol. 10, No. 3, pp.207 - 219.
2. Pfaffhuber, A.A. et al (2010). *Multi - method high resolution geophysical and geotechnical quick clay mapping.* Near Surface 2010 - 16th European Meeting of Environmental and Engineering Geophysics Zurich.
3. Bazin S. and Pfaffhuber, A.A. (2013). *Mapping of quick clay by electrical resistivity tomography under structural constraint*. Journal of Applied Geophysics 98, pp.280-287.
4. Rømoen, M., Pfaffhuber, A.A., Karlsrud, K. and Helle, T.E. (2010). *Resistivity on marine sediments retrieved from RCPTU-soundings: a Norwegian case study*. Proceedings, CPT'10, pp.289-296, Huntington beach, USA.

Technical reports:

1. Norwegian Geotechnical Institute (2009). *SIP12 - Correlation between horizontal and vertical resistivity measurements*. NGI report no.20081135-1, 15.09.2009. Client: Internal (NFR-SIP).
2. Norwegian Geotechnical Institute (2010). *Field monitoring of quick clay slope 2010. Data report – site investigations.* NGI report no.20100136-1-R, 22.07.2010. Client: Internal (NFR-SIP).

Enclosure B3

Tiller

The quick clay at Tiller test site has been used as a research material by NTNU for years. The area is located just south of Trondheim city, and the ground conditions consist of 8 m of non-sensitive clay over quick clay, see Figure B3.1. The soft Tiller clay is typical for the region, with an average water content (w), density (ρ_b) and plasticity (I_p) of 38 %, 18,9 kN/m^3 and 6,3 %, respectively. There is a tendency of reduced I_p with depth, particularly in the quick clay.

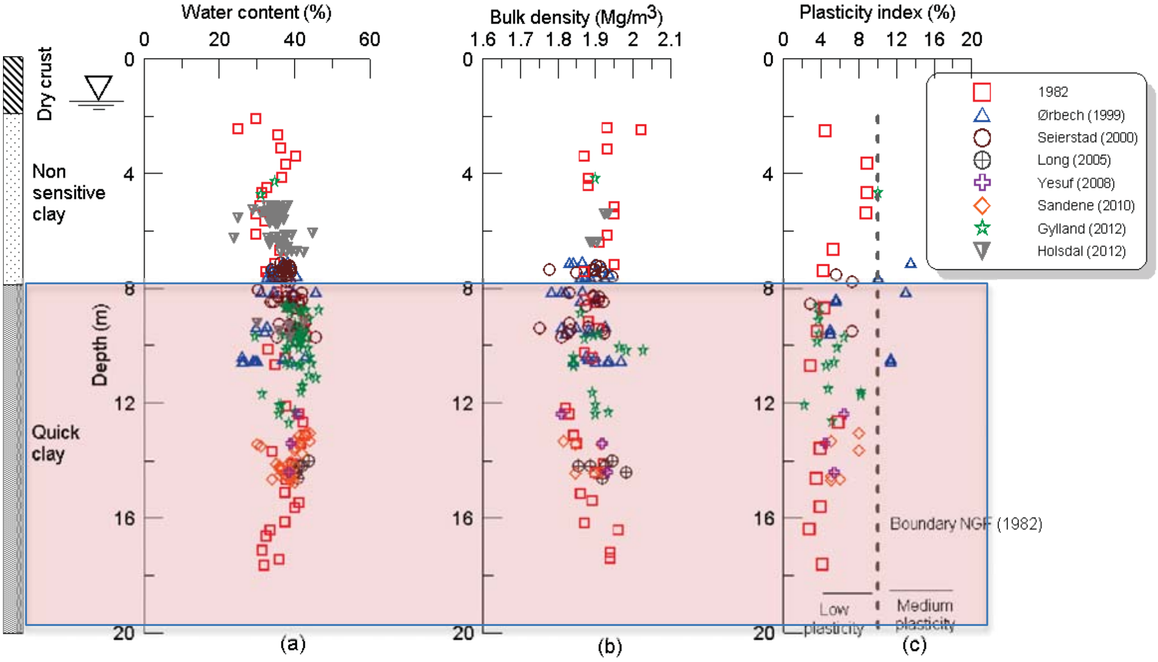


Figure B3.1. Tiller – basic index properties (all data from the area).

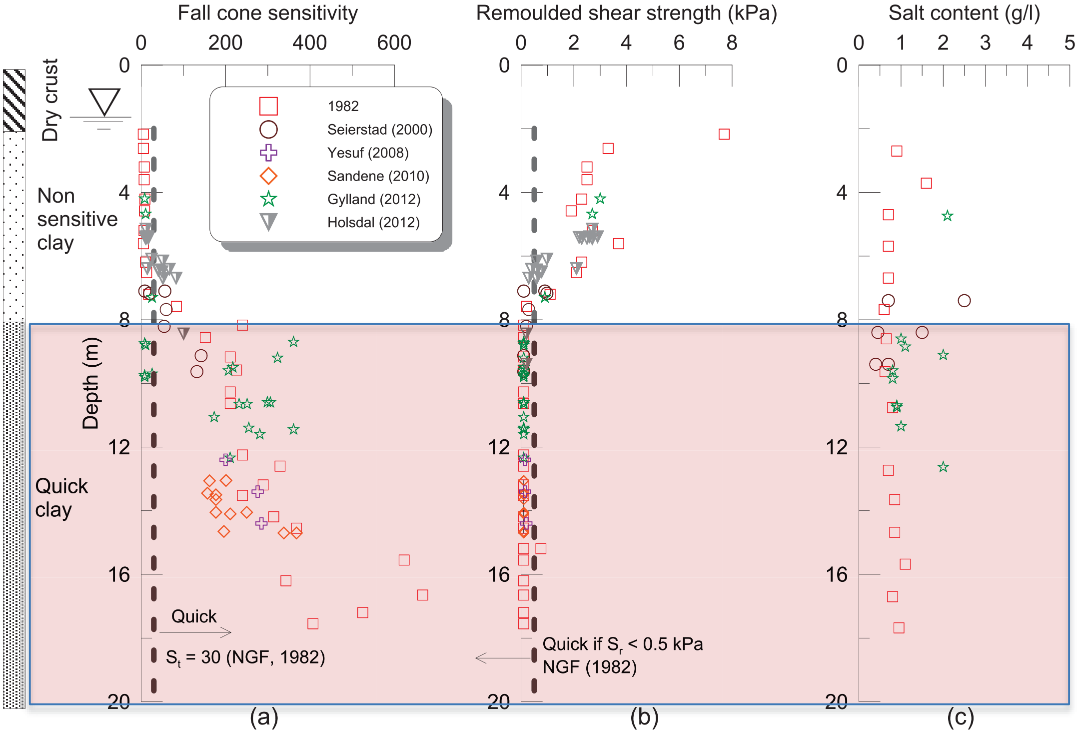
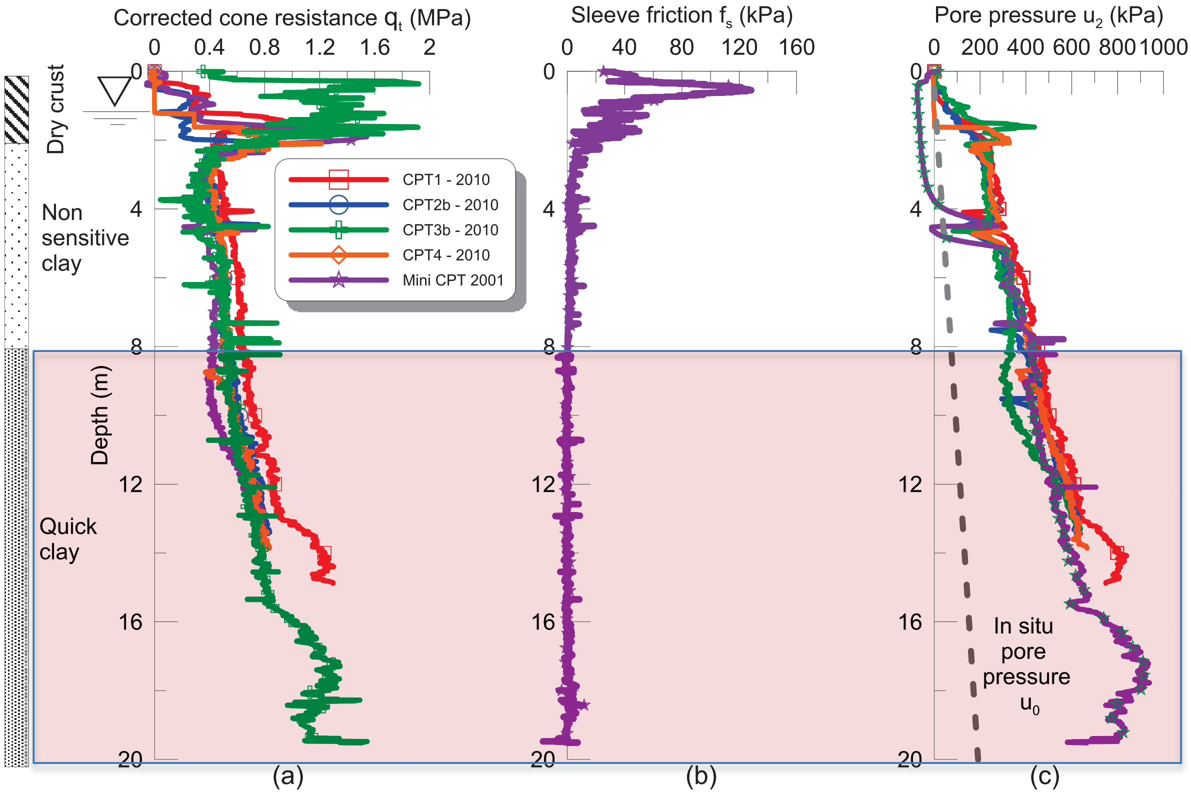


Figure B3.2. Tiller – sensitivity, remoulded shear strength and salt content (all data from the area).

The fall cone tests in Figure B3.2 show that the clay above 8 m depth is not sensitive, but that quick clay is encountered below this level. It is generally assumed that the sensitivity increases and the remoulded shear strength reduces by depth. There is good agreement between the various investigation methods used at the site. It is however interesting to note that there are no significant differences in water and salt contents between the non-sensitive and the quick clay. The porosity in the two layers is also quite similar. The non-sensitive layer seems to have been leached in the same way as the quick clay.

Selected CPTU data for the Tiller test site is shown in Figure B3.3. beneath the dry crust, the cone resistance is very low, but increases from ca. 400 kPa to ca. 1200 kPa at 20 m depth. The sleeve friction is very low, whereas the pore pressure increases linearly with depth, well above the hydrostatic distribution. There does not seem to be significant differences between the CPTU-recordings in the quick and non-sensitive layers, except for the sleeve friction which is very low in the quick clay layer.



(a) (b) (c)

Figure B3.3. Tiller – CPTU profile, q_t, f_s and u_2 (all data from the area).

A comparison between ERT and R-CPTU measurements for the area is shown in Figure B3.5. The R-CPTU tests were carried out in parallel tests, using probes of the same manufacture, and the test results are similar. The same is the case in comparison between the ERT and R-CPTU data, down to about 7 m. beneath this level, some discrepancies exist between the measurements, particularly below 12 m depth, where ERT gives higher resistivity values.

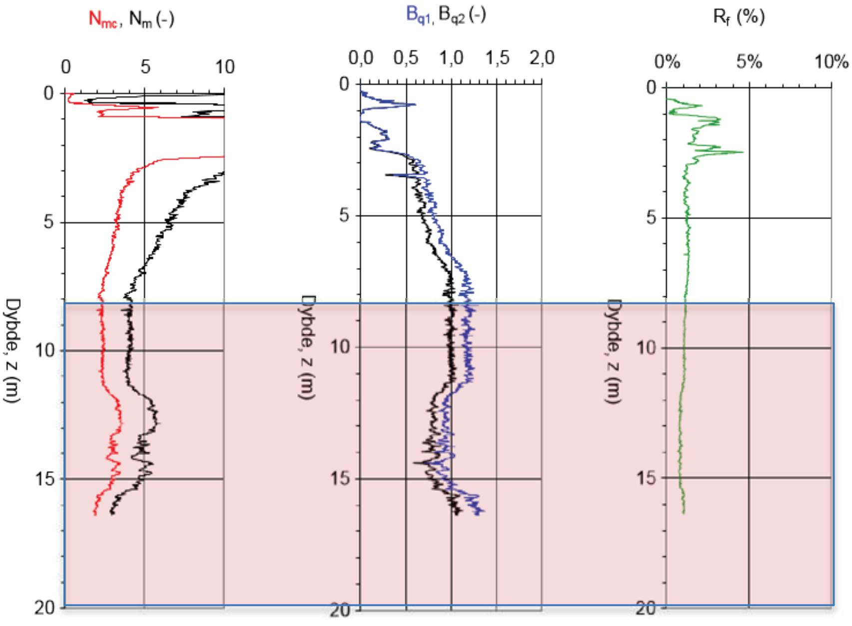


Figure B3.4. Tiller – CPTU profile, N_m, B_q, R_f (data from the whole area).

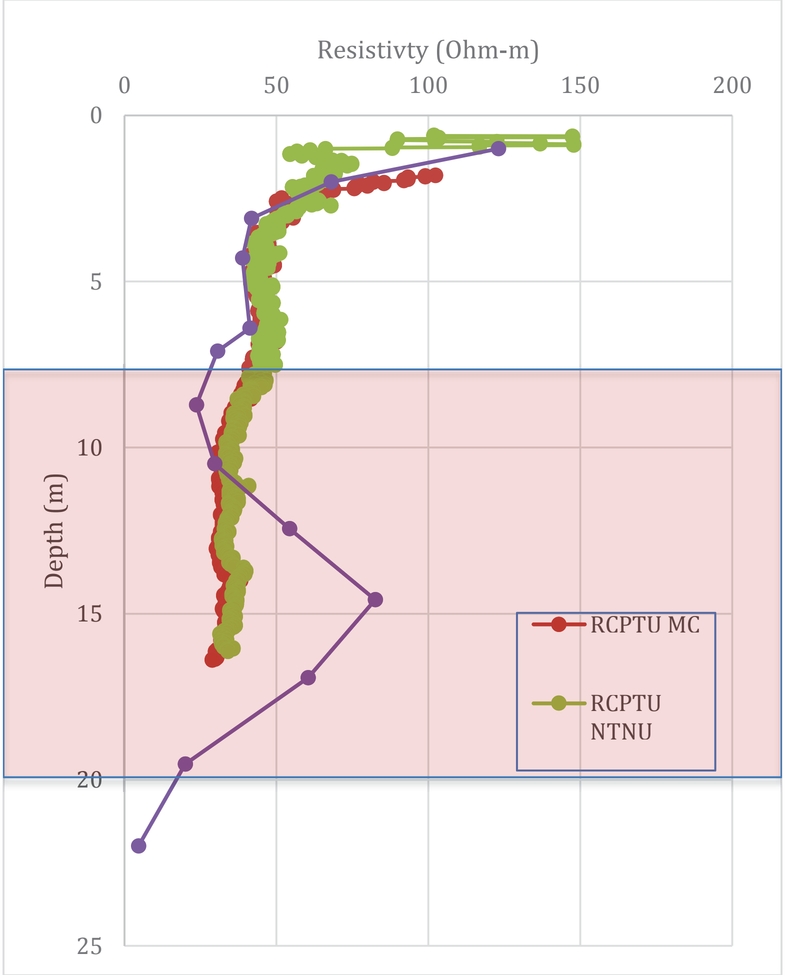


Figure B3.5. Tiller – comparison between ERT and R-CPTU measurements.

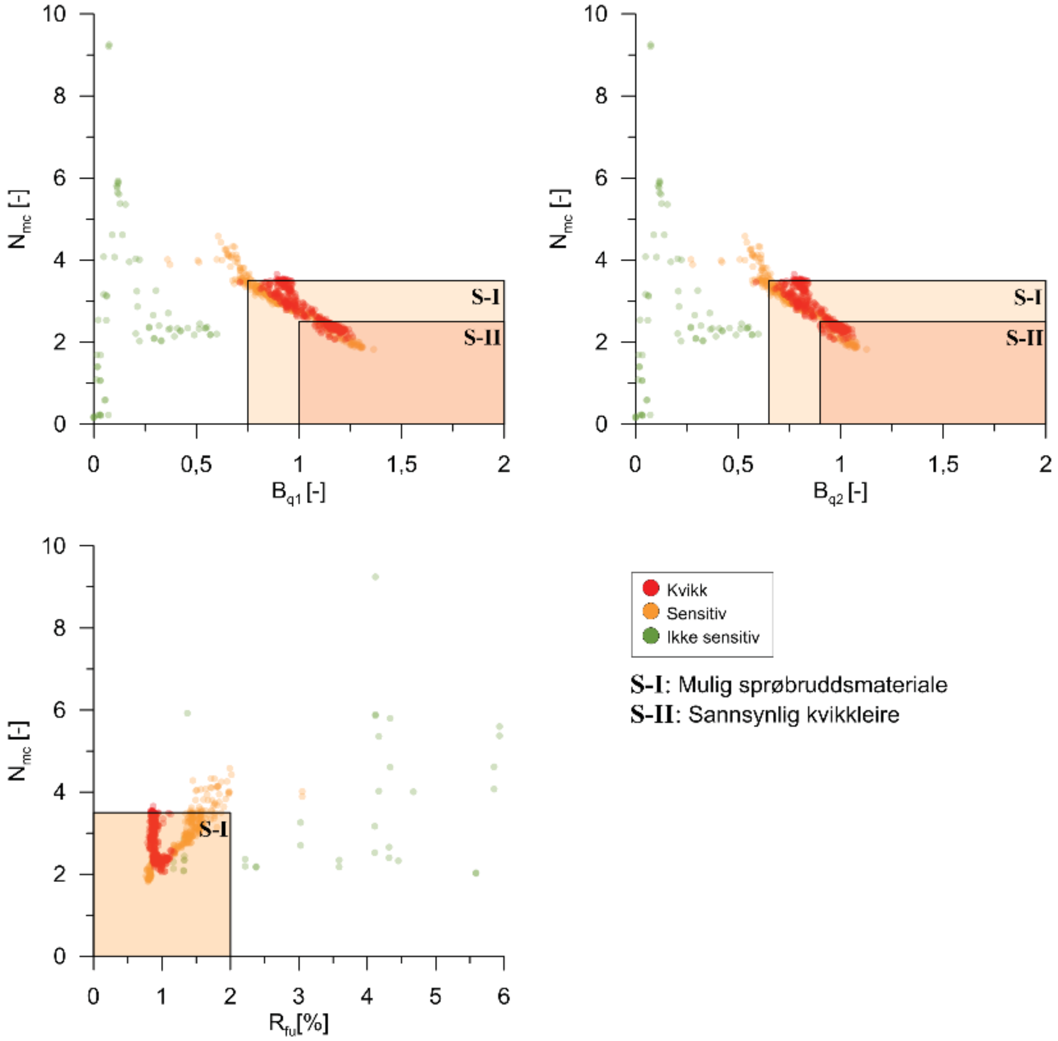


Figure B3.6. Tiller – new identification chart CPTU.

Important references

Publications:

1. Gylland, A. et al (2013). *Characterisation and engineering properties of Tiller clay.* Engineering Geology (Elsevier), Vol. 164, pp.86 - 100.
2. Sandven, R. et al (2004). *Sample disturbance in highly sensitive clay.* Proceedings of the 2nd International Conference on Geotechnical and Geophysical Site Characterisation - ISC'2. Porto. Millpress, Rotterdam, pp.1861-1868.

PhD- and Master theses:

1. Sandven, R. (1990). *Strength and deformation properties of fine grained soils obtained from piezocone tests.* PhD dissertation, Geotechnical department, NTH (now NTNU), Trondheim.
2. Puakowski, S. (2015). *Interpretation methods of CPTU and R-CPTU with special focus on soft soils in Norway*. Master thesis, Department of Civil and Transport Engineering, NTNU, Trondheim.
3. Ørbech, T. (1999). *Sample disturbance in clays and silts in Norwegian)*. Master theses, Geotechnical department, NTH (now NTNU), Trondheim

Enclosure B4

Esp, Byneset

The test site at Esp was investigated thoroughly after the slide accident in December 2012, and both quick and non-sensitive clays are found in the area, see Figure B4.1. The properties correspond to that of Tiller clay, with an average water content of w = 39%, average density (ρ) of 18,5 kN/m^3 and plasticity I_p = 8%. The clay content is relatively low, with an average of 35,7%.

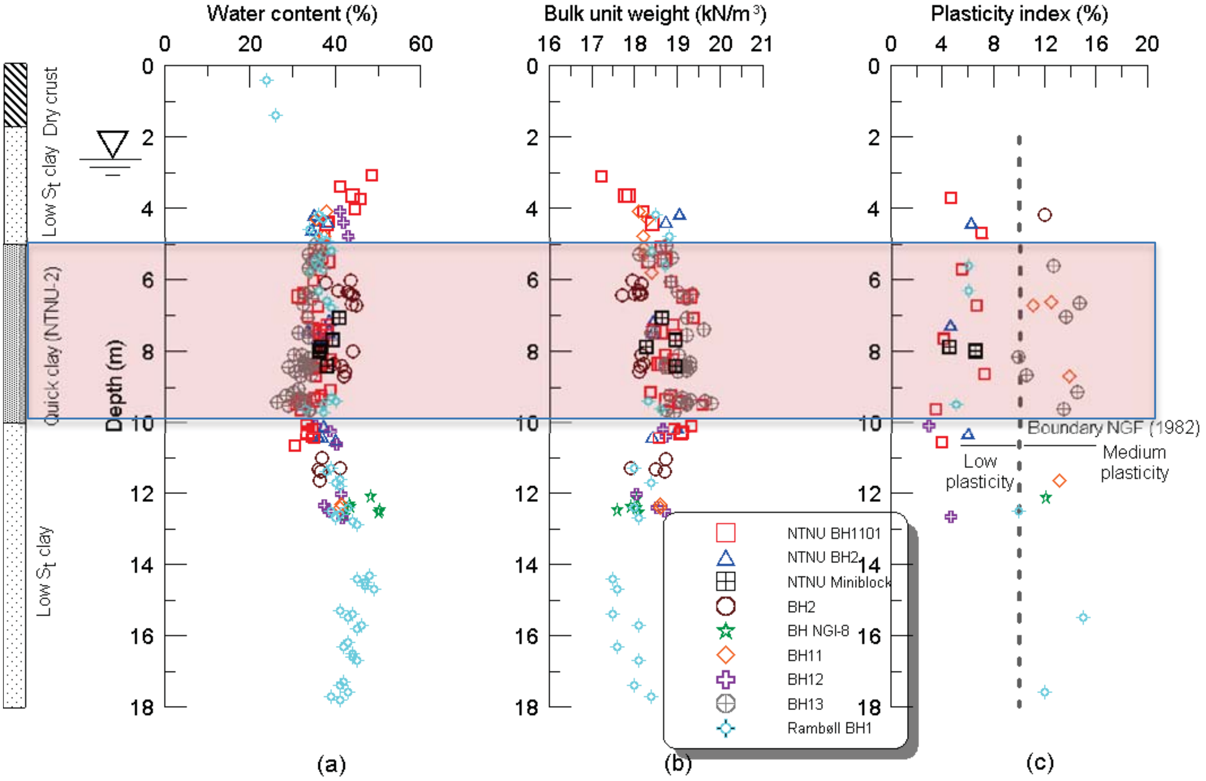


Figure B4.1. Esp, Byneset – basic index properties (all boreholes in the area).

In this study, results from the boreholes BH NTNU2 and Rambøll BH 1 have been emphasized. At these locations, a quick clay layer is found between ca. 5,5 m and 10,5 m depth, see Figure B4.2. As for Tiller clay, low salt content values are found both in quick and non-sensitive layers.

CPTU data for this test site are characteristic for this material, with a corrected cone resistance (q_t) increasing from about 400 kPa in the top of the soft clay layer, to about 1100 kPa at 17 m depth. The sleeve friction (f_s) is generally very low, in the order of 5 kPa. The pore pressure (u_2) increases linearly by depth, and is considerably larger than the hydrostatic value, see Figur B4.4.

R-CPTU and ERT data are compared in Figure B4.5. The agreement between the measurements is generally very good. The ERT-measurements are similar to the R-CPTU results, except for a quick clay zone between 6 and 8 m where the ERT-values are higher.

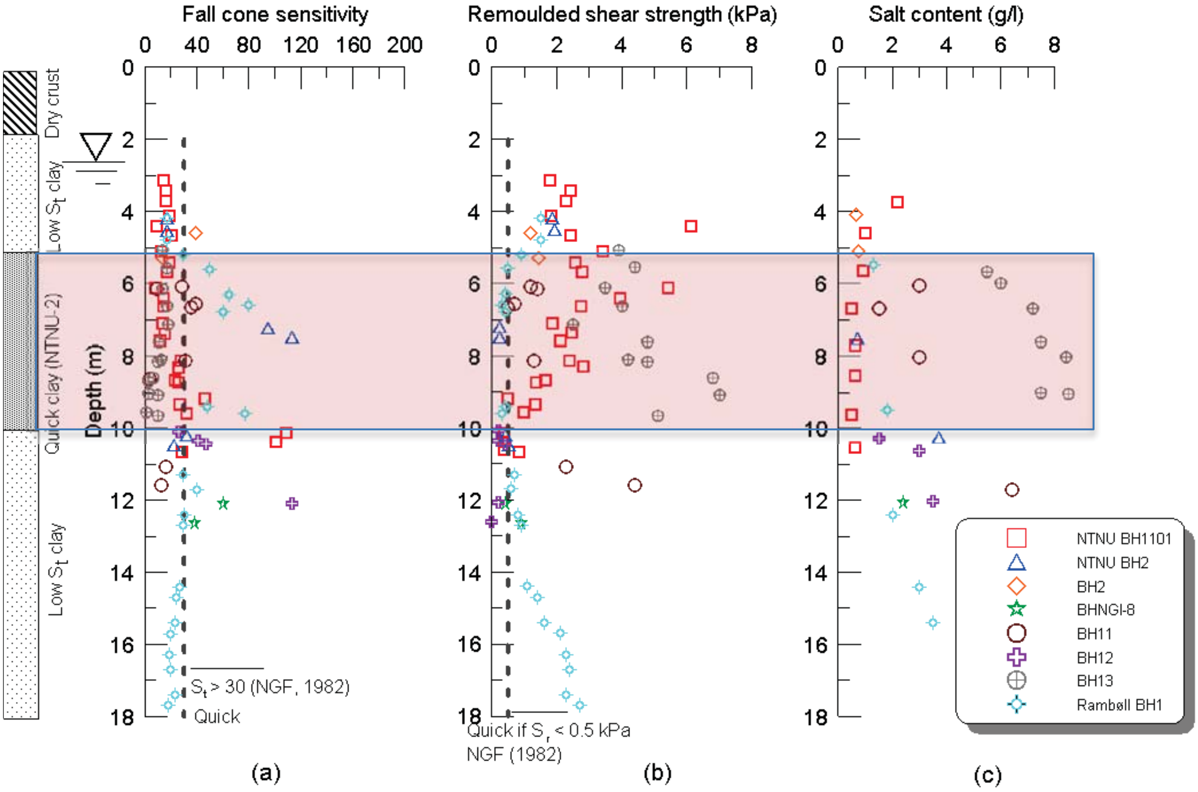


Figure B4.2. Esp, Byneset – sensitivity, remoulded shear strength and salt content (all boreholes).

Figure B4.3 shows a comparison between rotary pressure (DRT) and total sounding profiles (TOT) for borehole BH NTNU2. The profiles give relatively unique and similar identification of the quick clay layer between 5,5 and 10,5 m, where the slope of penetration force curve is constant (vertical slope). The total sounding profile is in this case somewhat disturbed by adding of new rods, but the general impression is a constant or slightly decaying penetration force. By magnitude, the penetration force is somewhat higher for the total sounding due to a higher rod diameter and use of drillbit instead of a twisted tip.

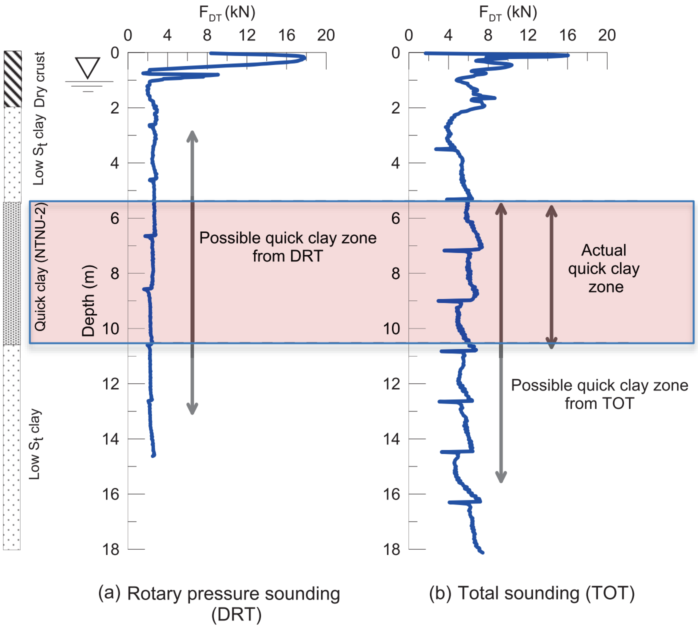


Figure B4.3. Esp, Byneset – comparison between rotary pressure sounding (DRT) and total sounding (TOT) (BH NTNU2).

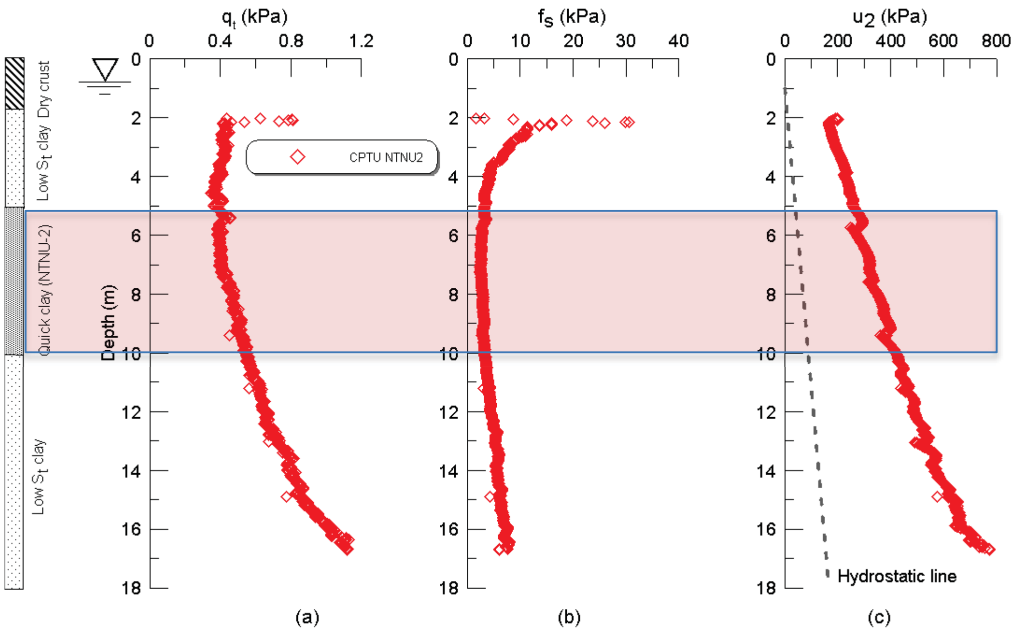


Figure B4.4. Esp, Byneset – CPTU data, q_t, f_s and u_2 (BH NTNU2).

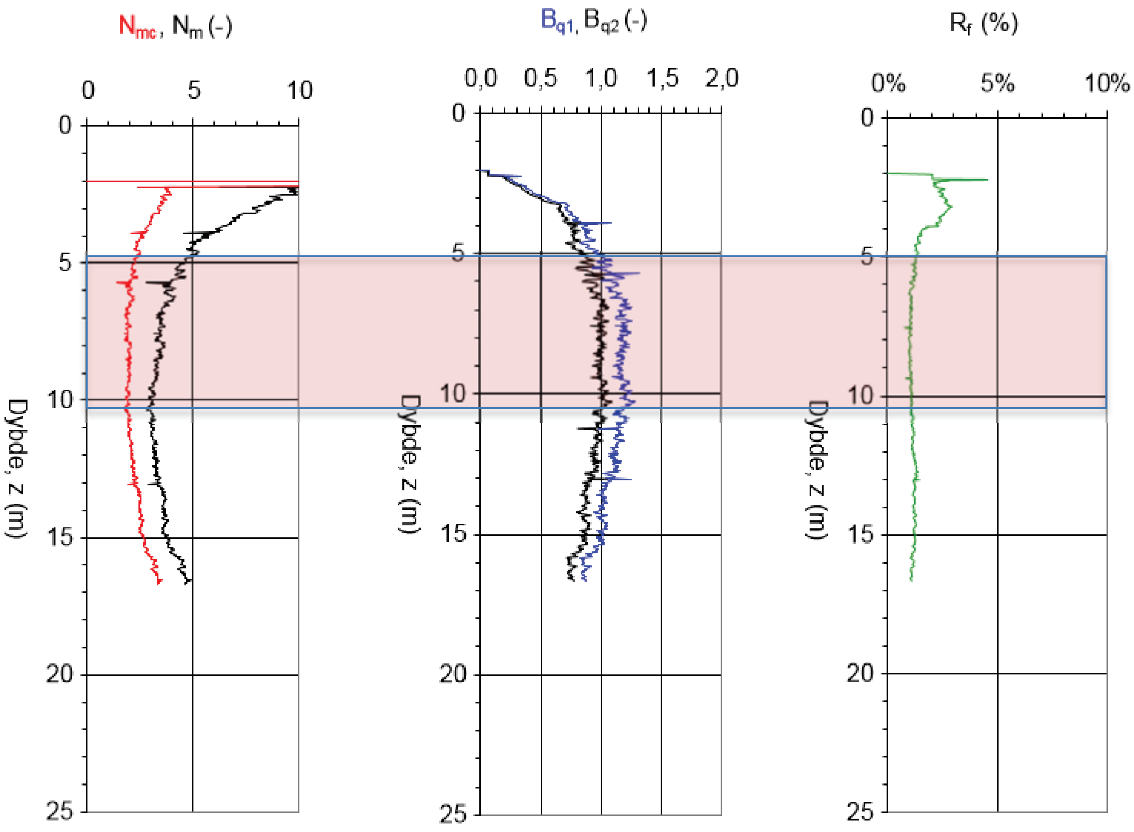


Figure B4.5. Esp, Byneset – CPTU data, N_m, B_q, R_f (BH NTNU2).

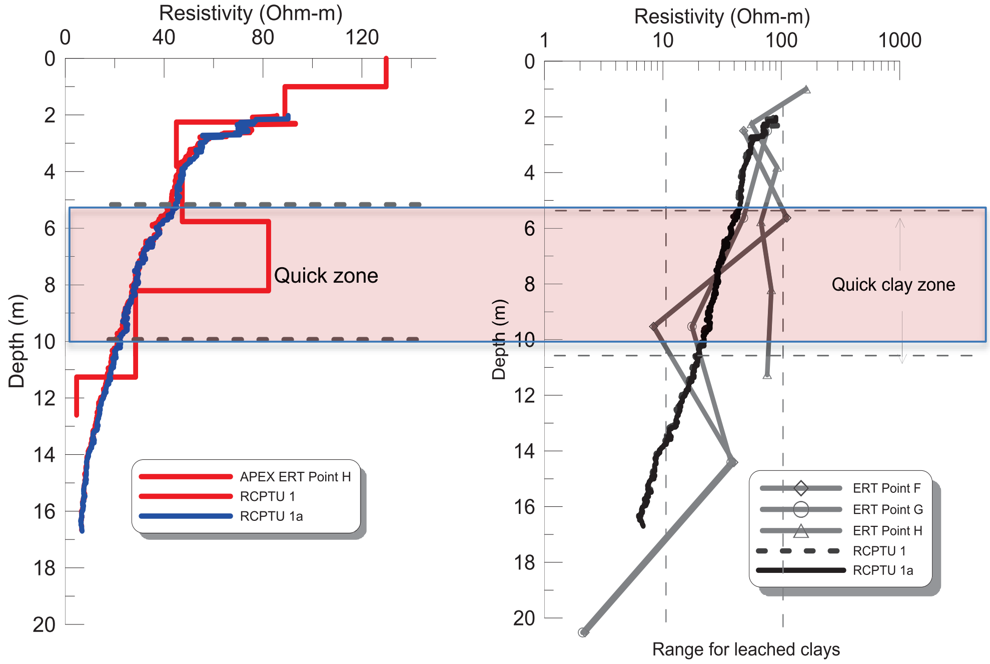


Figure B4.6. Esp, Byneset - (a) comparison between ERT and R-CPTU measurements (BH NTNU2).

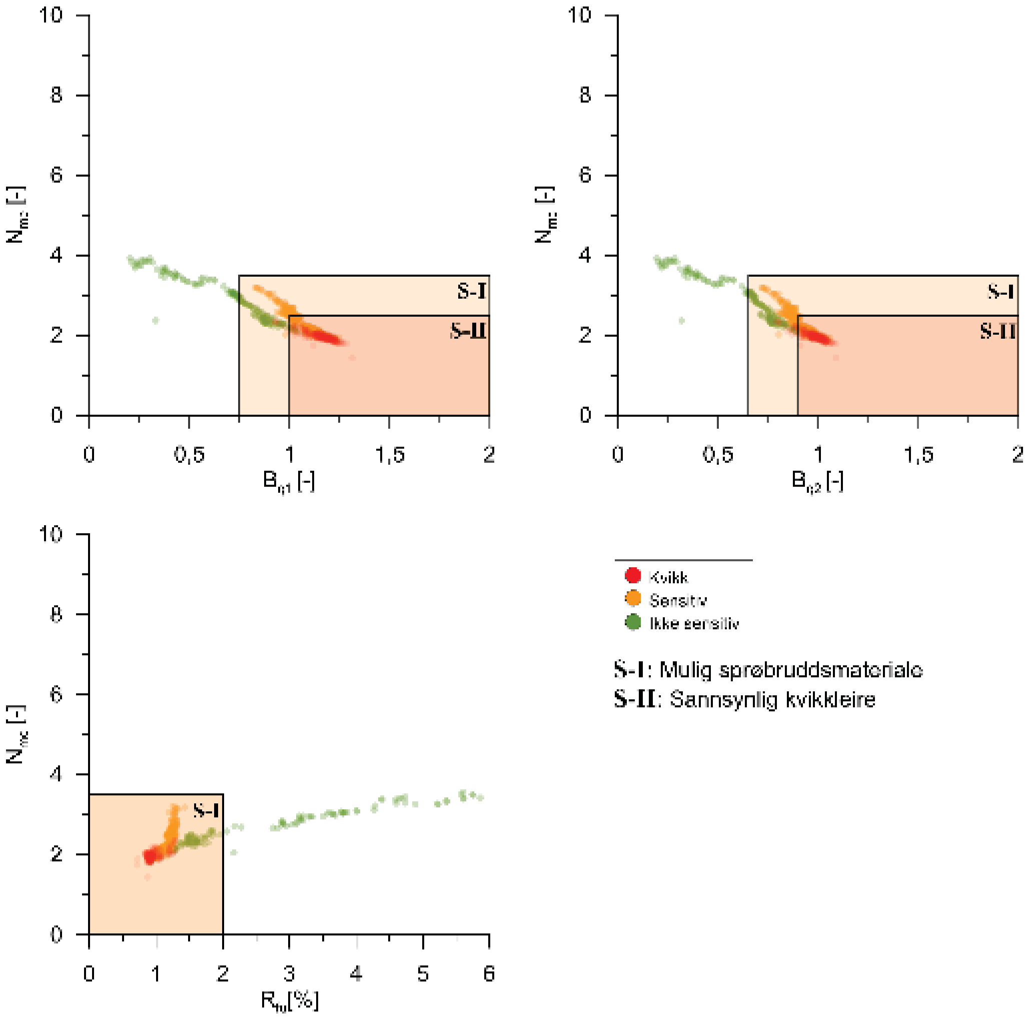


Figure B4.7. Esp, Byneset – new identification chart CPTU (BH NTNU2).

Important references

Publications:

1. Lyche, E. (2012). *The quick clay slide at Esp, Byneset in 2012 (in Norwegian)*. Statens vegvesen (NPRA), Teknologidagene 2012.

Technical reports:

1. Thakur, V. (2012). *Data report from the quick clay slide at Esp, Byneset (in Norwegian)*. Norges Vassdrags- og Energidirektorat (NWRED), Statens vegvesen (NPRA) and Jernbaneverket (NNRA). NIFS report no. 34/2012.

Master theses:

1. King, J. (2013). *Testing of clays at landslide site at Esp, Byneset*. Master thesis, Department of Civil and Transport Engineering, NTNU.
2. Hundal, E. (2014). *CPTU with measured total sounding resistance. New possibilities for detection of quick clay? (In Norwegian),* Master thesis, Department of Civil and Transport Engineering, NTNU.
3. Montafia, A. (2013). *Influence of physical properties of marine clays on electric resistivity and basic geotechnical parameters*. Master thesis, Department of Civil and Transport Engineering, NTNU, Trondheim.

Enclosure B5

Klett south

The Klett test site was developed by Statens vegvesen (NPRA), NGI and Multiconsult as a part of the new E6 South highway project. The test site is located south of the existing E6 highway at Klett south of Trondheim. A corresponding test site is located north of E6 and is described in Enclosure B6. Several aspects of the behavior of quick clay have been investigated in this study, including use of CPTU and R-CPTU, as well as electrical field vane testing. Average water content w is lower than the Tiller clay (w = 32%), whereas the average density ρ is higher (ρ=1,95 g/cm^3). The average I_p is relatively similar to that of Tiller clay, averaging 5,8% (in BH1503).

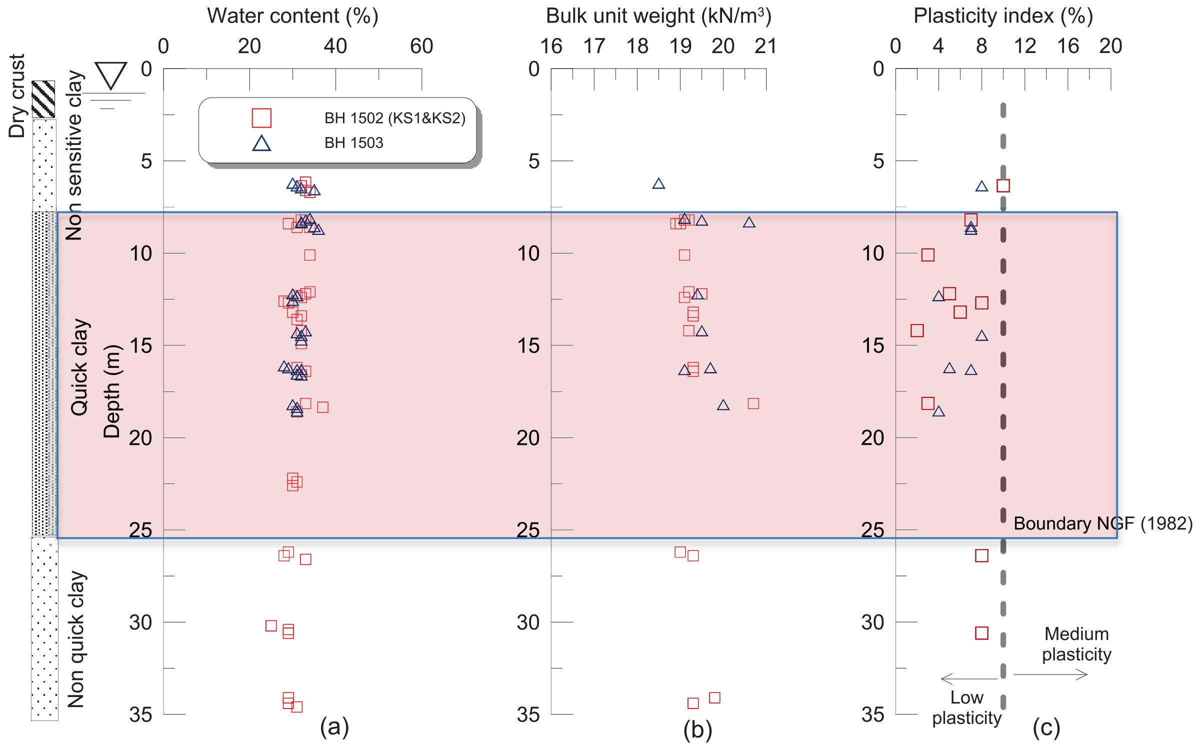


Figure B5.1. Klett south – basic index properties.

The test site contains non-sensitive clay to about 6 m - 8 m, with quick clay below this level, see Figure B5.2.

CPTU data for the boreholes KS1 and KS2 show very good repeatability, see Figure B5.4. The corrected cone resistance (q_t) increases from about 500 kPa at the top of the soft clay layer to about 2000 kPa at 35 m depth. The sleeve friction (f_s) is low, but shows a slight increase by depth and at the top of the quick clay layer. The pore pressure is generally high and well above a hydrostatic pore pressure distribution.

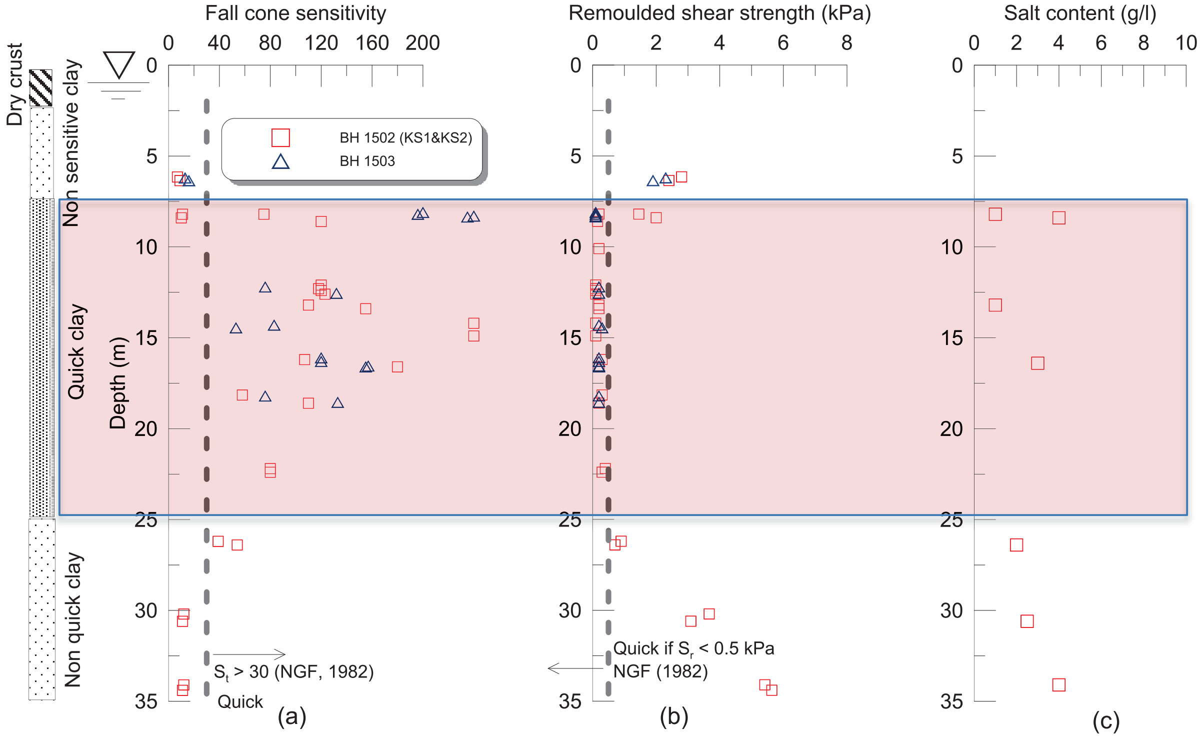


Figure B5.2. Klett south – sensitivity, remoulded shear strength and salt content.

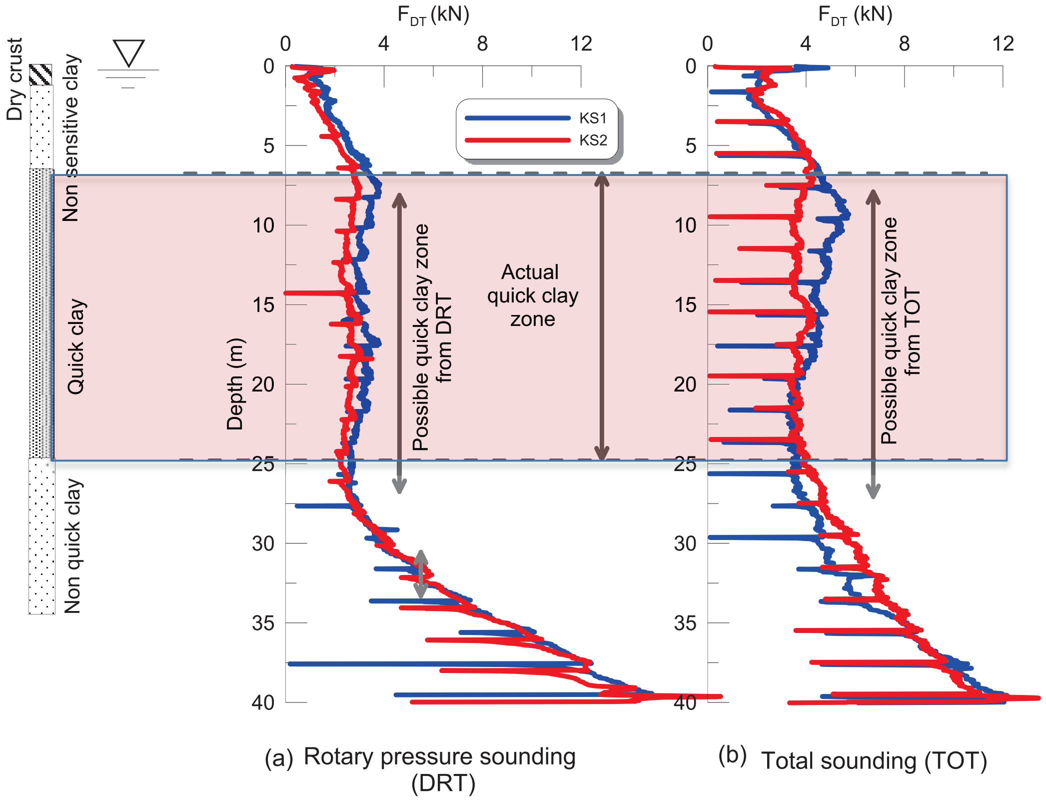


Figure B5.3. Klett south – comparison between rotary pressure and total sounding profiles.

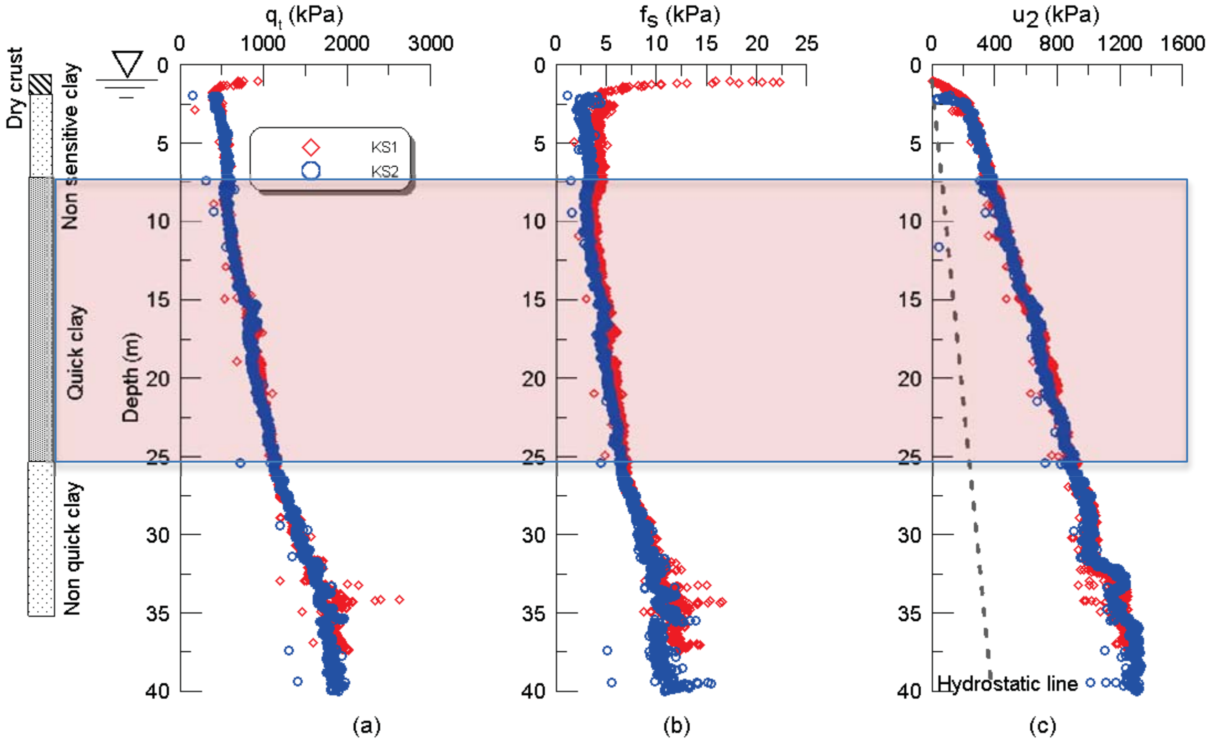


Figure B5.4. Klett south – CPTU data, q_t, f_s and u_2.

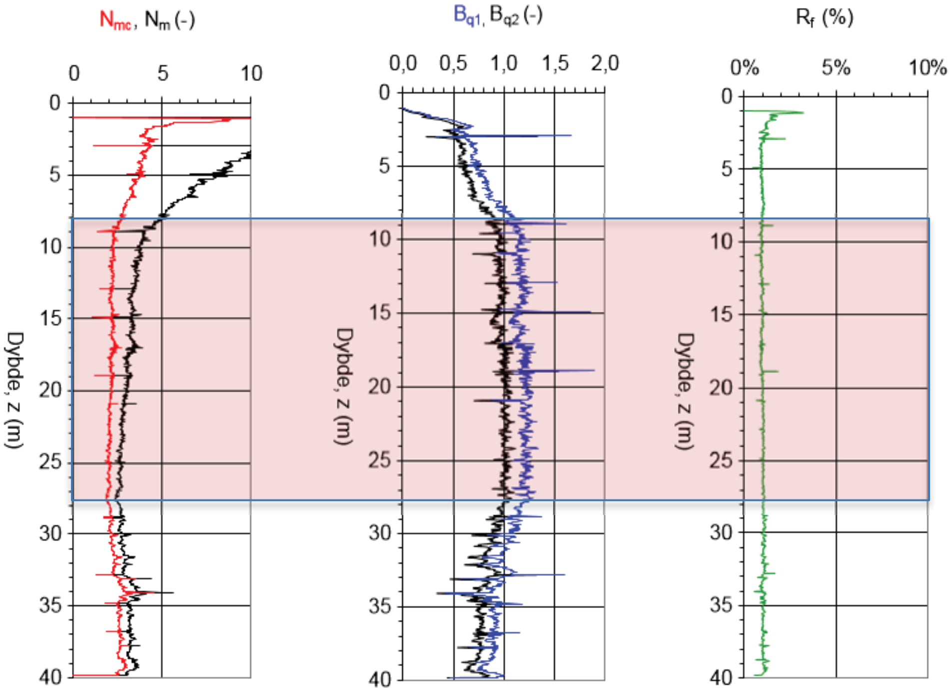


Figure B5.5. Klett south – CPTU data, N_m, B_q, R_f.

In general, there is good agreement between R-CPTU and ERT measurements at the two locations KS1 and KS2, see Figure B5.6.

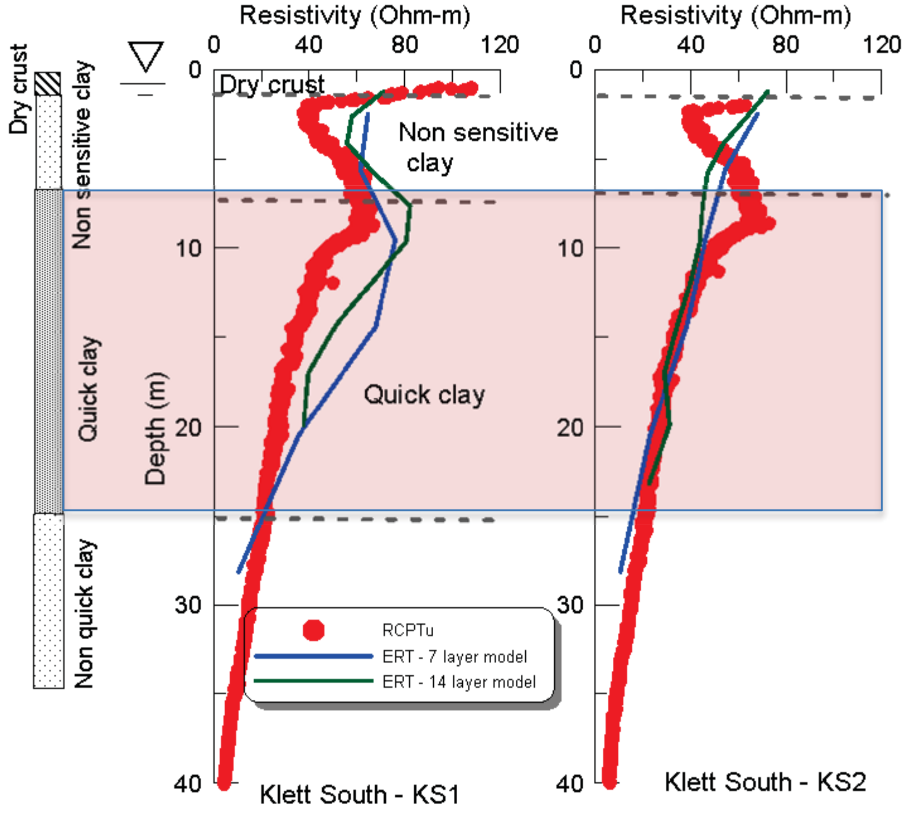
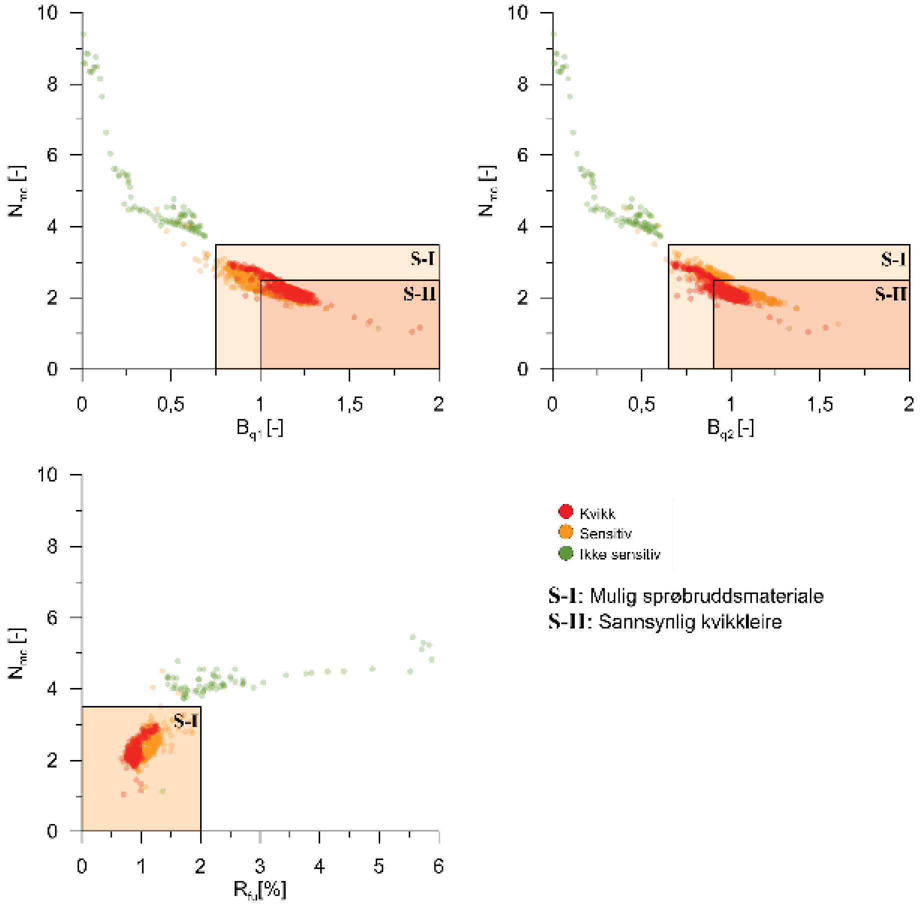


Figure B5.6. Klett south – a) comparison between ERT and R-CPTU measurements.



S-I: Mulig sprøbruddsmateriale
S-II: Sannsynlig kvikkleire

Figure B5.7. Klett south – new identification chart CPTU.

Important references

Publications:

1. Amundsen, H.A. et al (2015). *On engineering characterisation of a low-plastic sensitive soft clay.* Proceedings, GeoQuebec 2015 – Challenges from North to South. Québec, Canada.

Technical reports:

1. Multiconsult (2015). *Detection of quick clay by R-CPTU and electric field vane tests. Results from field study*.
   Multiconsult report no. 415559-2-RIG-RAP-003rev01.
   NIFS report no. R101-2015.

Enclosure B6

Klett north

The test site at Klett north is not fully investigated as by yet. The test site is however interesting because laboratory data from block samples are available, together with ERT and R-CPTU data. The basic index test data are summarized in Figure B6.1. The average values of w, ρ_b and I_p are 33,1 %, 19,3 kN/m^3 and 8,7 %, respectively. For all practical relations, the ground conditions are hence quite similar to those of the Klett south test site.

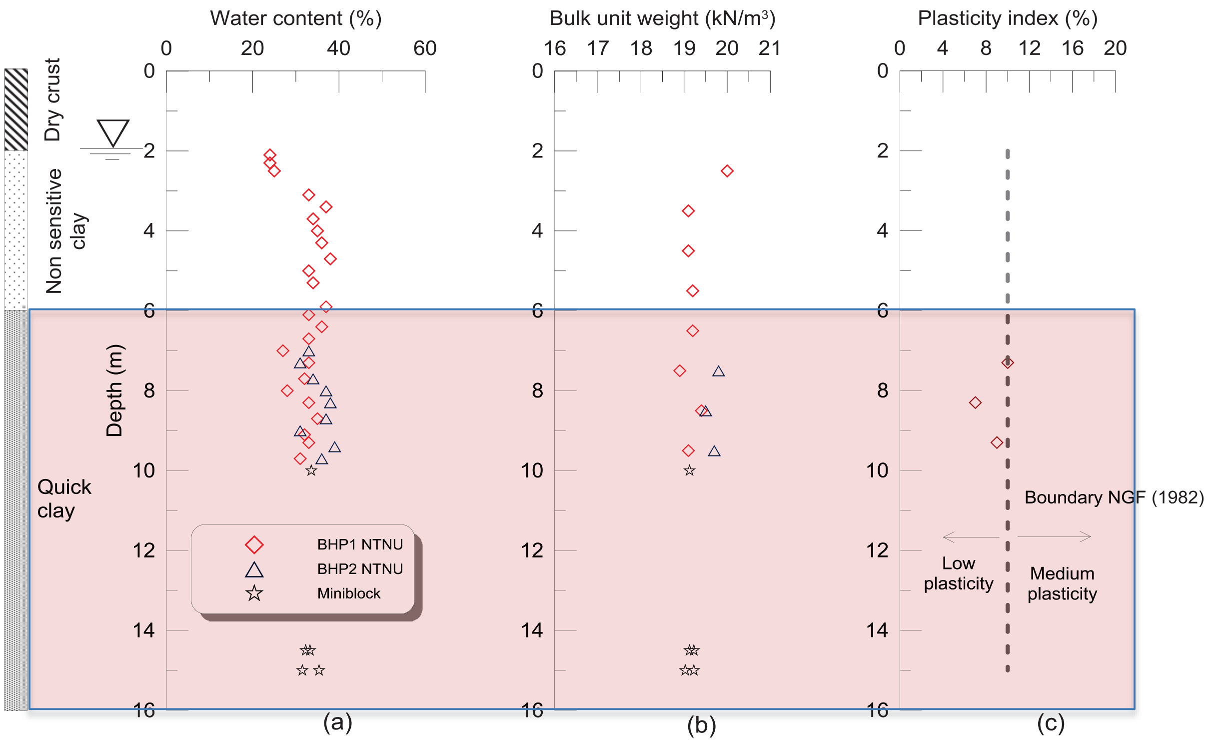


Figure B6.1. Klett north – basic index properties.

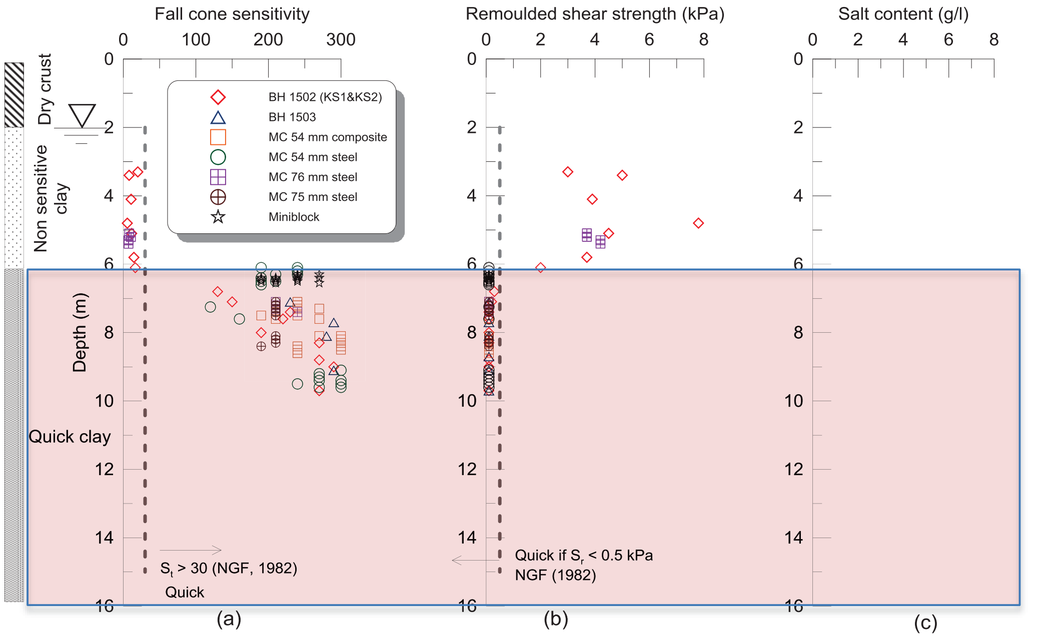


Figure B6.2. Klett north – sensitivity, remoulded shear strength and salt content (not carried out).

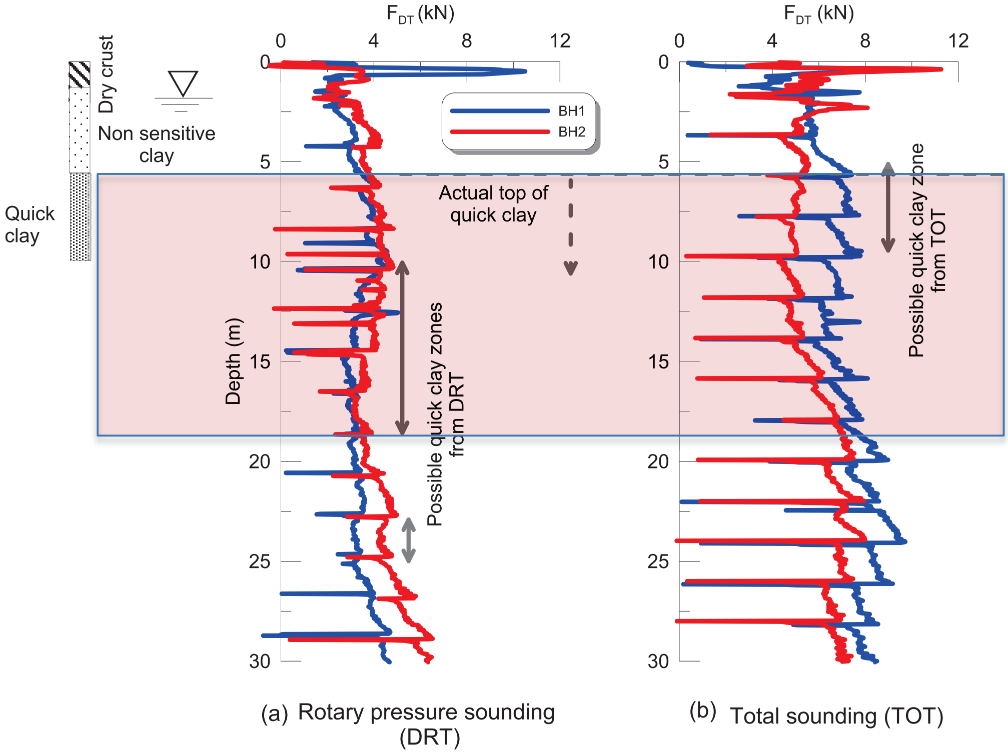


Figure B6.3. Klett north – comparison between rotary pressure- and total sounding profiles.

For the Klett north test site it is easier to define the ground conditions due to a large amount of samples, see Figure B6.2. The conditions can be by a 2 m thick top crust over non-sensitive, plastic clay down to about 4 m depth, then quick clay down to ca. 10 m.

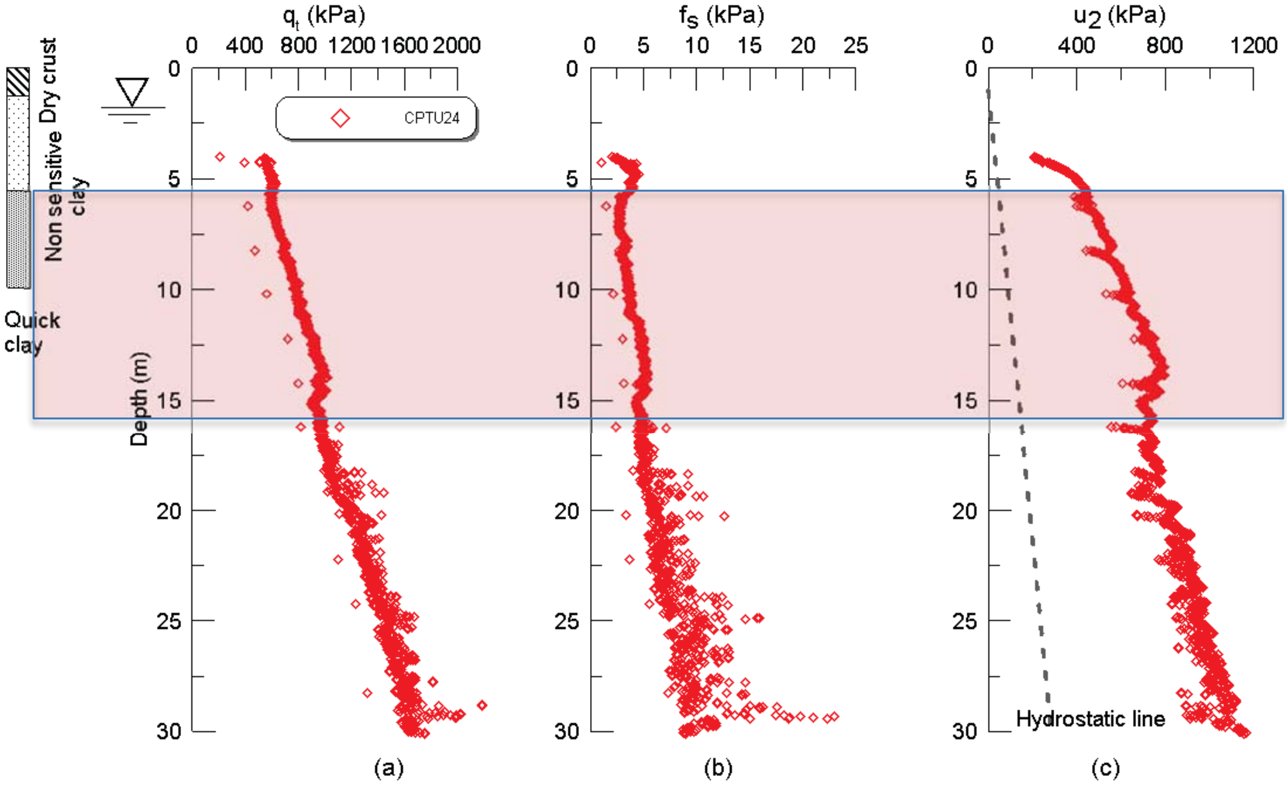


Figure B6.4. Klett north – CPTU data, q_t, f_s and u_2.

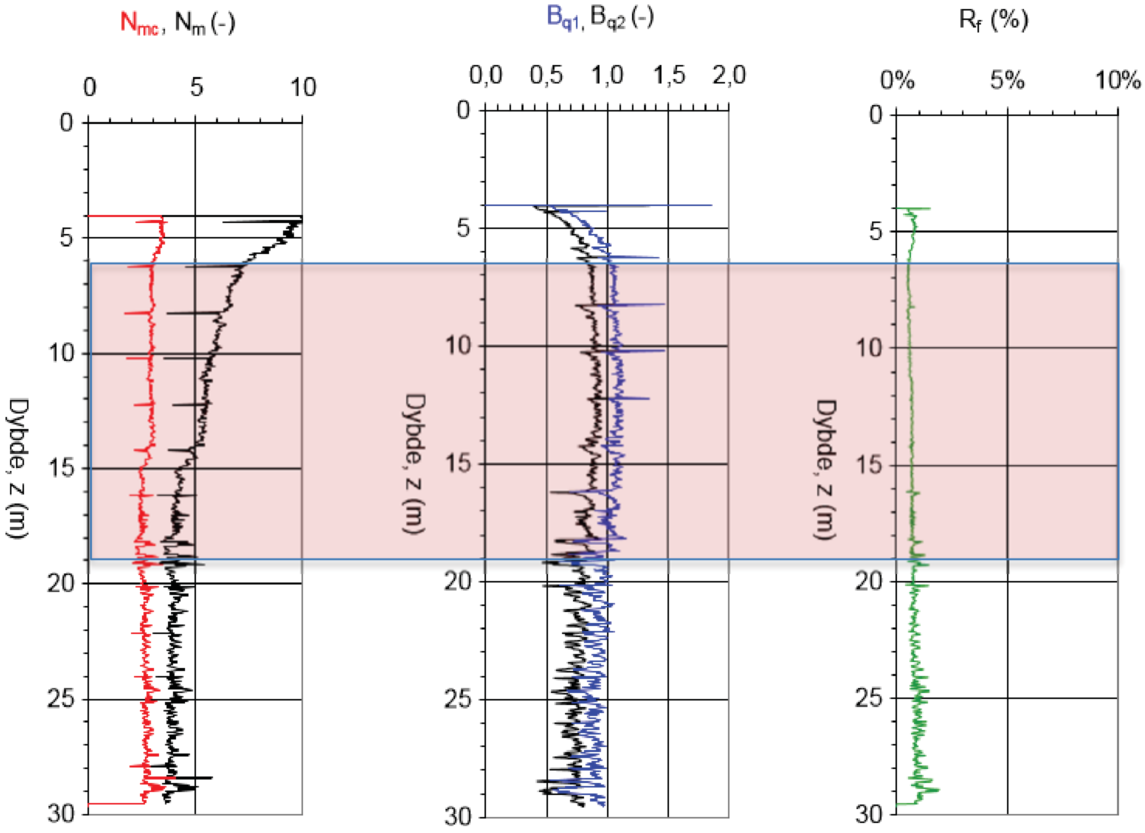


Figure B6.5. Klett north – CPTU data, N_m*,* B_q*,* R_f*.*

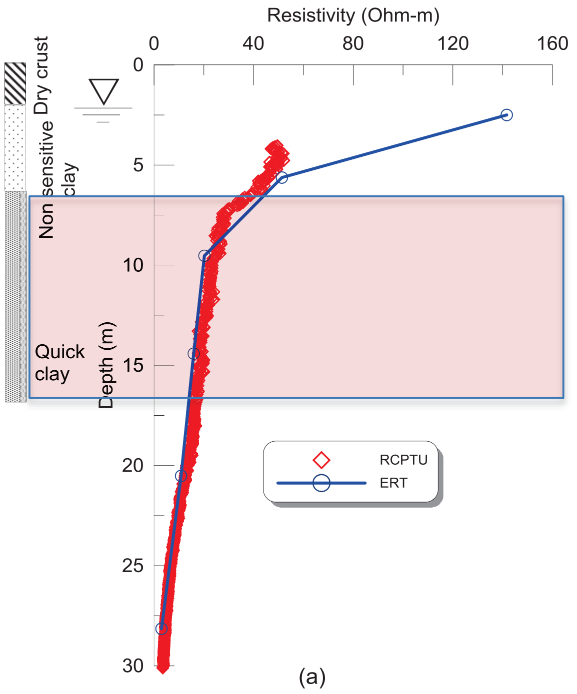
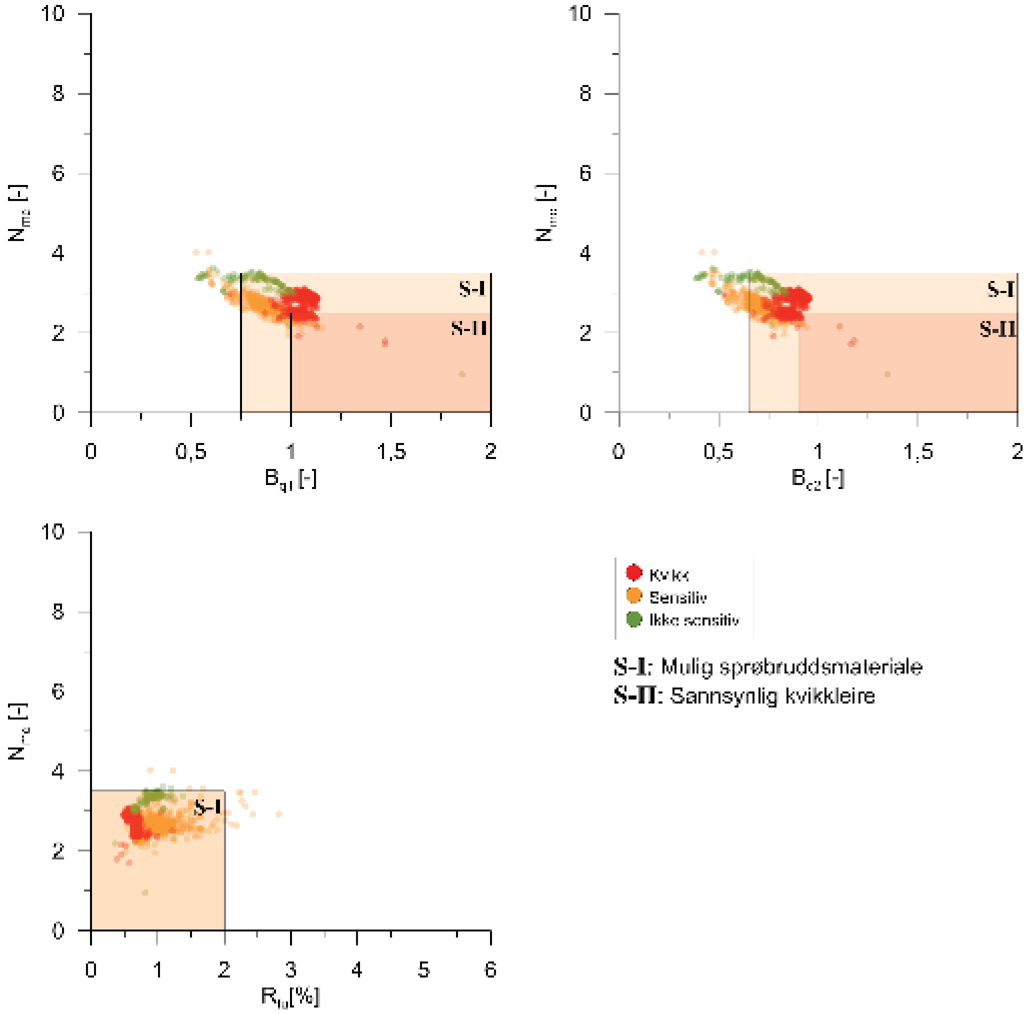


Figure B6.6. Klett north – comparison between ERT and R-CPTU measurements.



S-I: Mulig sprøbruddsmateriale
S-II: Sannsynlig kvikkleire

Figure B6.7. Klett north – new identification charts CPTU.

CPTU profiles for Klett north are quite similar to those of Klett south, see Figur B6.4, with q_t values somewhat larger and with more variations due to a higher content of silt and sand lenses. The variations are visible in the profiles for sleeve friction f_s and pore pressures u_2, particularly below 15 m. Similar to the Klett south profiles, there is a change in the f_s-profile on top of the quick clay layer.

ERT and R-CPTU data for Klett north are compared on Figure B6.6. The agreement between the methods is very good, both in quick and non-sensitive layers.

Important references

Technical reports:

1. Sandven, R. (2014). *Summary of field results (in Norwegian)*. Course note NGF Seminar on sampling and laboratory tests, May 2014 (www.ngf.no).

Enclosure B7

Dragvoll (Research area salt diffusion)

The research site Dragvoll is used in a PhD study on salt diffusion for treatment of quick clay (PhD student Tonje Eide Helle). The ground conditions in the area consists of about 4,5 m non-sensitive clay over quick clay, see Figure B7.1. The quick clay is very soft and difficult to sample and prepare in the laboratory. Average values for w and ρ are 36,6 % and g 18,8 kN/m^3, respectively. The average plasticity I_p for Dragvoll clay is 5,5 %, which represents a lower plasticity compared to the other test sites.

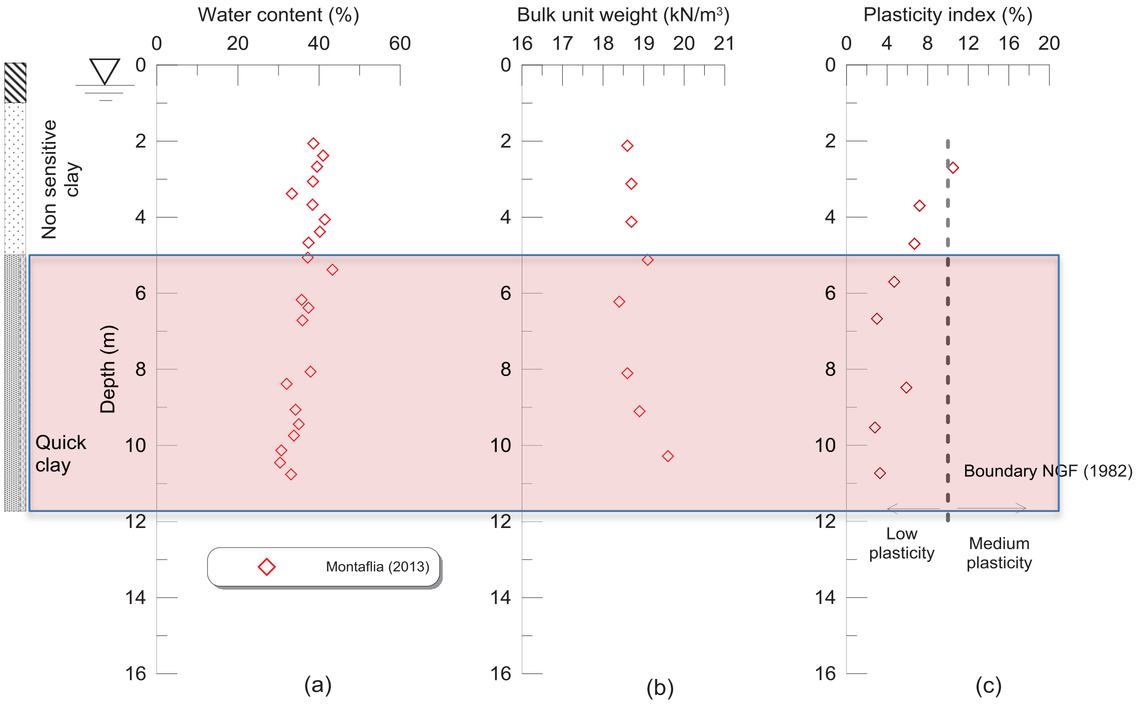


Figure B7.1. Dragvoll – basic index properties.

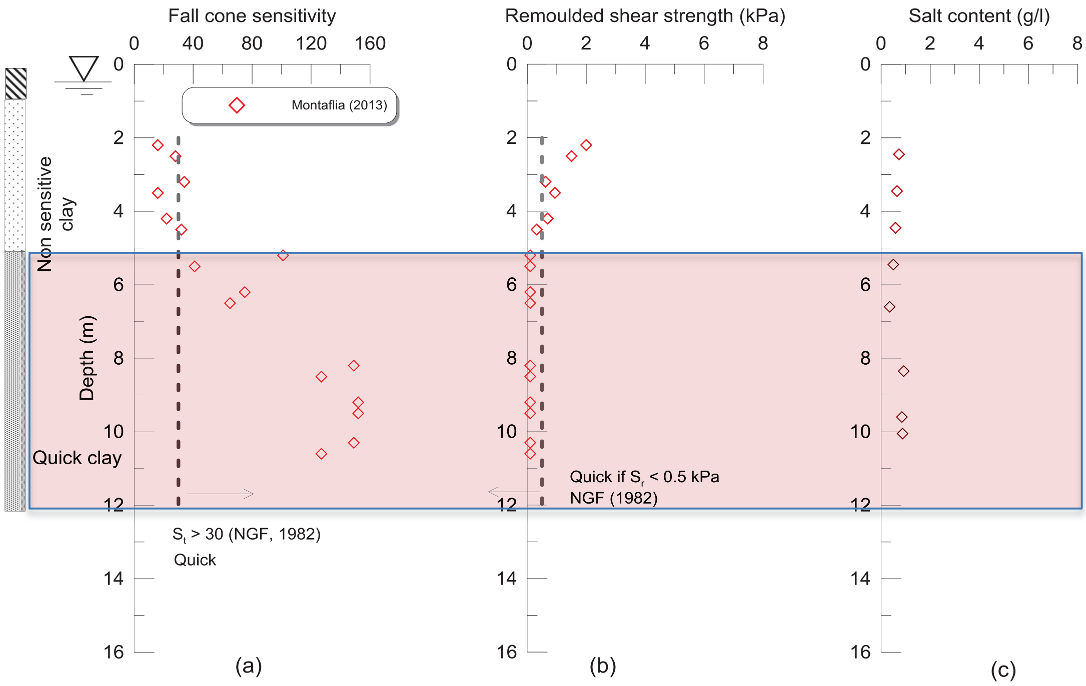


Figure B7.2. Dragvoll – sensitivity, remoulded shear strength and salt content.

Similar to the results at the test sites Tiller and Esp, the salt content is low in the clay layers. The non-sensitive clay layer has apparently been leached, similar to the deep layer of quick clay.

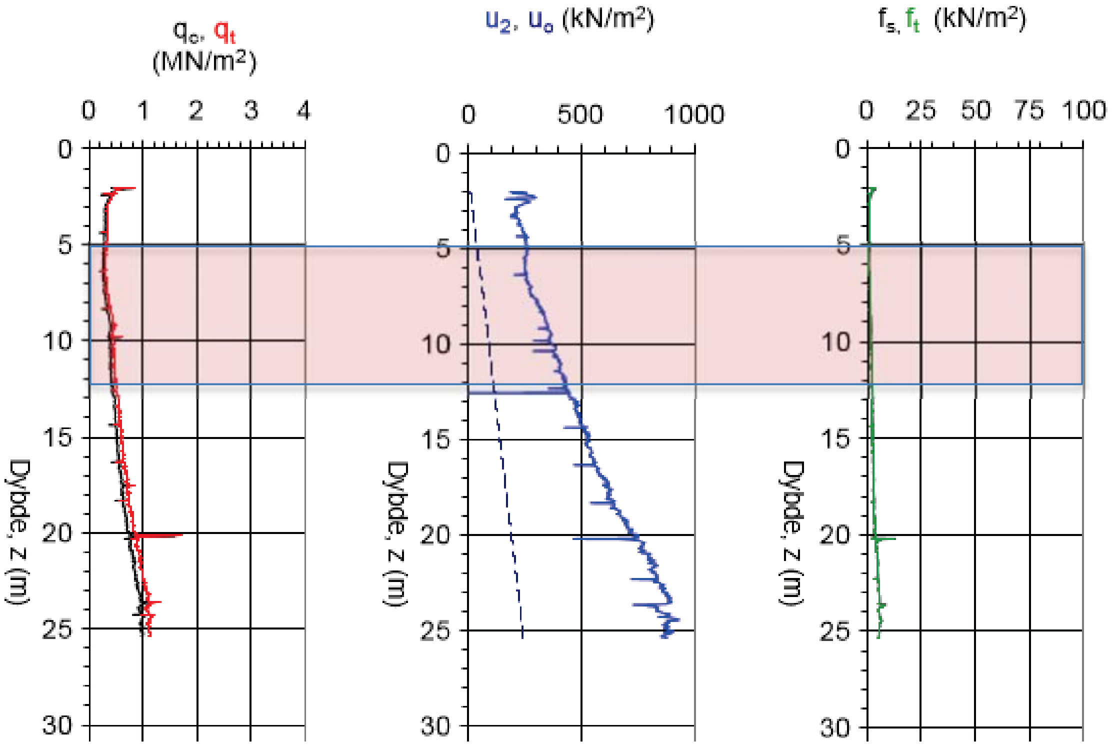


Figure B7.3. Dragvoll – CPTU profile, q_t, f_s and u_2.

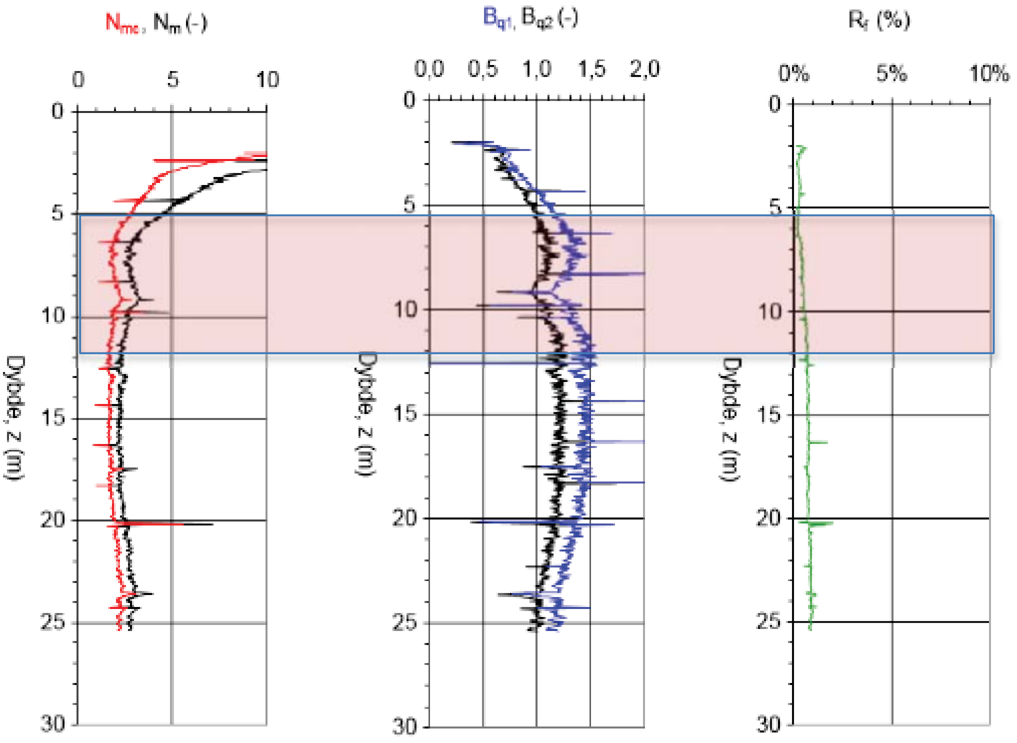


Figure B7.4. Dragvoll – CPTU profile, N_m, B_q, R_f.

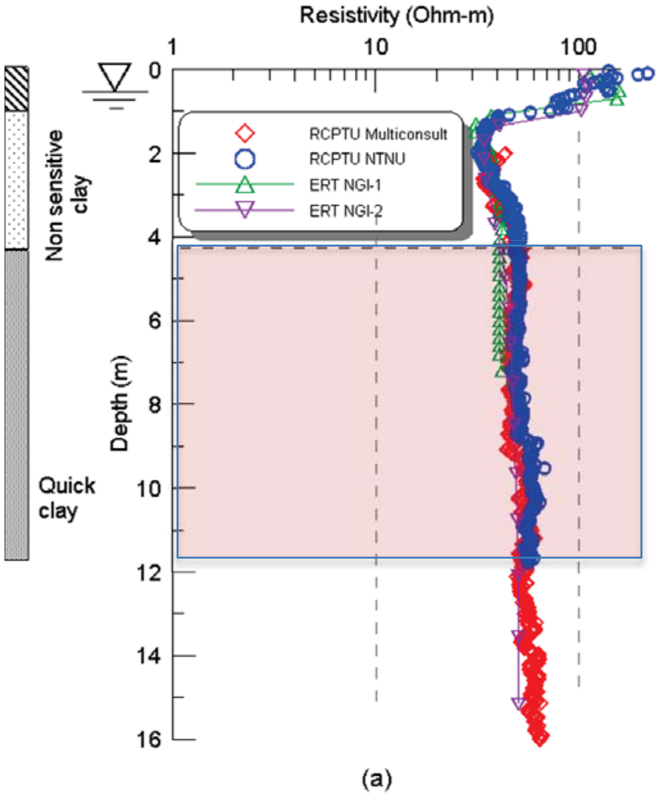


Figure B7.5. Dragvoll – comparison between ERT and R-CPTU measurements.

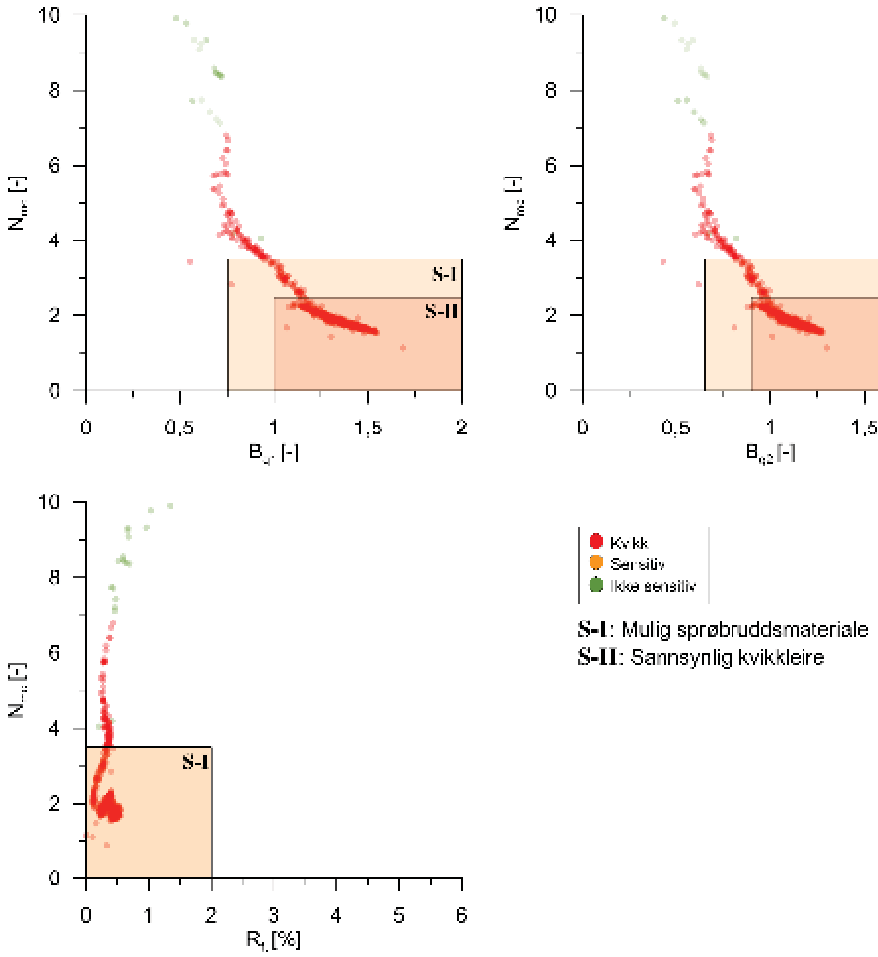


Figure B7.6. Dragvoll – new identification chart CPTU.

CPTU data for the Dragvoll test site are shown in Figure B7.3. The cone resistance values are remarkably small and increases from about 300 kPa to about 1000 kPa with depth. The sleeve friction values are also extremely low and signal a quickly that easily becomes fully liquefied by remoulding. The pore pressure is remarkably higher than the hydrostatic value. The slope of the curves for q_t, f_s and u_2 data does not seem to change at the boundary between quick to non-sensitive material.

ERT and R-CPTU measurements for the Dragvoll site are compared in Figure B7.5. The electrode spacing for the ERT-measurements was very small (0,5 m), which gives very good resolution in the profile. Very good agreement exist between the two methods, both in quick and non-sensitive clay.

Important references

Publications:

1. Eide – Helle, T. et al (2015). *Laboratory setup to evaluate the improvement of geotechnical properties from potassium chloride saturation of a quick clay from Dragvoll, Norway*. GEOQuébec 2015 - Challenges from North to South. Québec, Canada.
2. Emdal, A. et al (2012). *Characterisation of Quick Clay at Dragvoll, Trondheim, Norway*. Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 43, No. 4 (December), pp.11 - 23.

Master theses:

1. Montafia, A. (2013). *Influence of physical properties of marine clays on electric resistivity and basic geotechnical parameters*. Master thesis, Department of Civil and Transport Engineering, NTNU, Trondheim.

Enclosure B8
Fallan

The Fallan test site is located in the municipality of Melhus, east of E6 and approximately 5 km north – northeast of the village Lundamo. The test site was developed by Multiconsult in 2012 as a part of a feasibility study for a new road line in the area (Haga – Skjerdingstad). The actual test site is located in an area with marine deposits, situated between two ridges of rock, Valderåsen and Rognbrauta. The whole area is a part of an enormous slide pit after a large quick clay slide, taking place in 1665.

As basis for the feasibility study, site investigations were carried out along the planned road line. Statens vegvesen (NPRA) performed field investigations with total soundings, pore pressure measurements, ϕ54 mm piston sampling and cone penetration tests with pore pressure measurements (CPTU). Multiconsult and Statens vegvesen shared the laboratory investigations between them, including index tests, triaxial- and oedometer tests. NTNU carried out determination of salt content on samples from all cylinders. An overview of the most commom index parameters is shown in Figure B8.1.

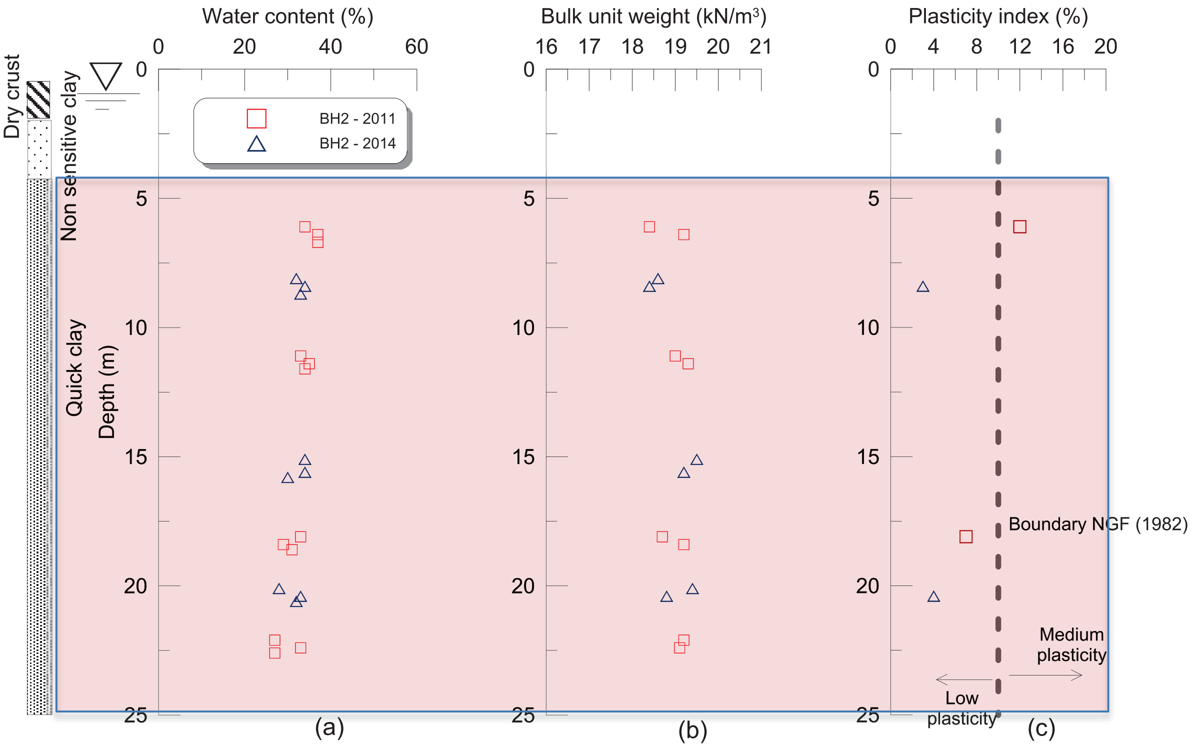


Figure B8.1. Fallan – basic index properties.

The ground investigations show that the ground consists of a thin top crust of organic material with thickness between 0,5 and 2,0 m. Below this layer, thick deposits of marine sediments are encountered, with soft and partly sensitive/quick clay over large parts of the area. The quick clay layer range from about 4 m below the terrain surface, down to about 22,5 m depth, see Figure 8.2. The clay seems to be homogeneous, but with some layers and pockets of silt.

The water content is between 30 % and 35 % and slightly decrease by depth. The density varies between 1,92 and 1,95 g/cm^3, whereas the plasticity is between 5 and 10 %. Classification values of the undrained shear strength from fall cone and unconfined compression tests increase approximately linearly with depth, whereas the sensitivity generally plots between 50 and 110. The salt content varies between 0,4 and 0,9 g/l which should normally represent quick clay.

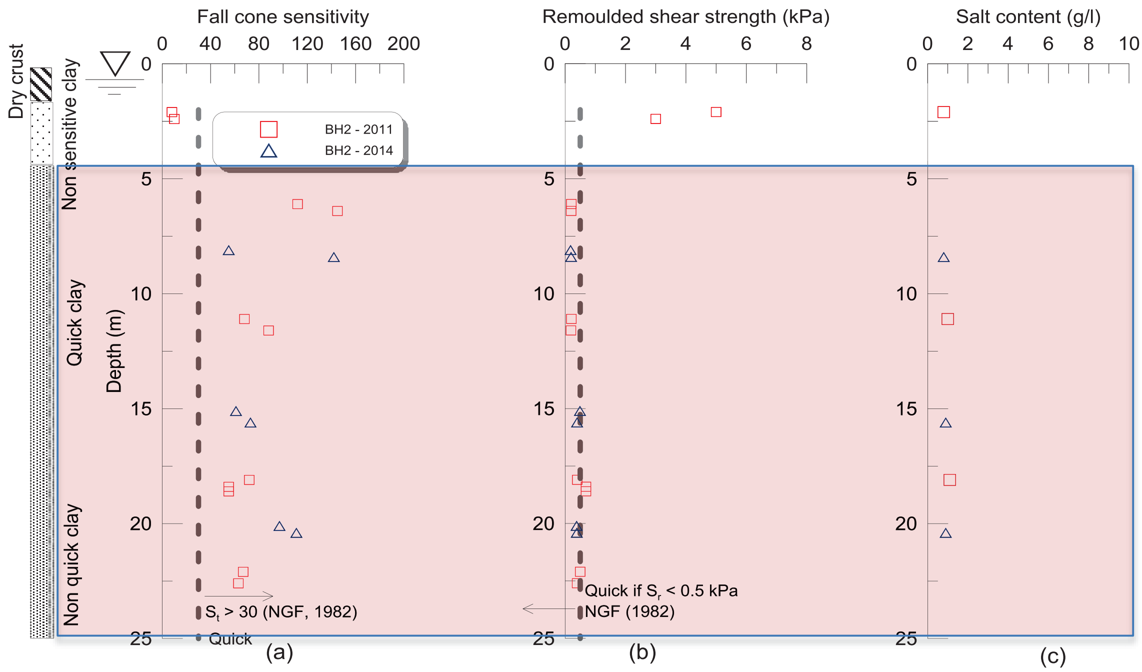
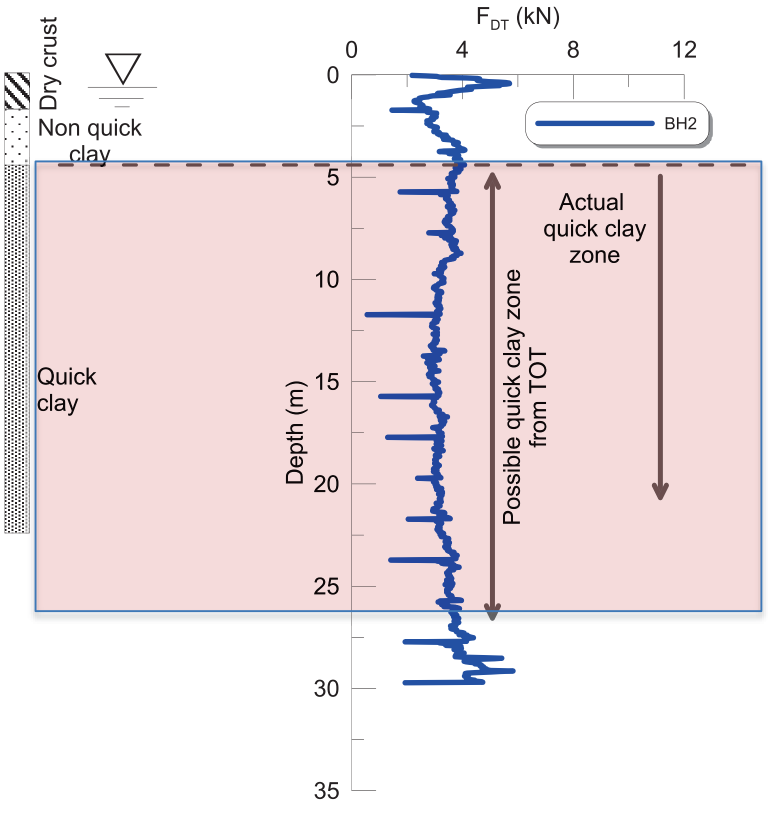
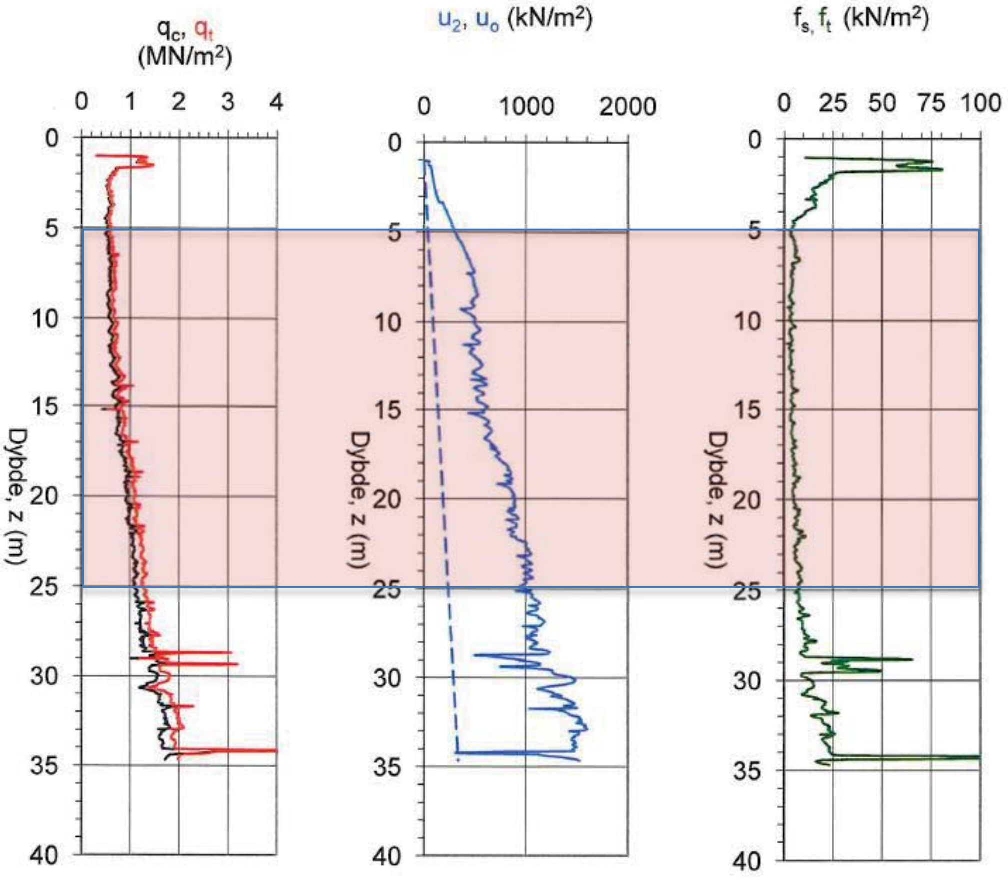


Figure B8.2. Fallan – sensitivity, remoulded shear strength and plasticity.



(a) Total sounding (TOT)

Figure B8.3. Fallan – total sounding profile.



Figur B8.4 Fallan – CPTU profiles, q_t, f_s and u_2.

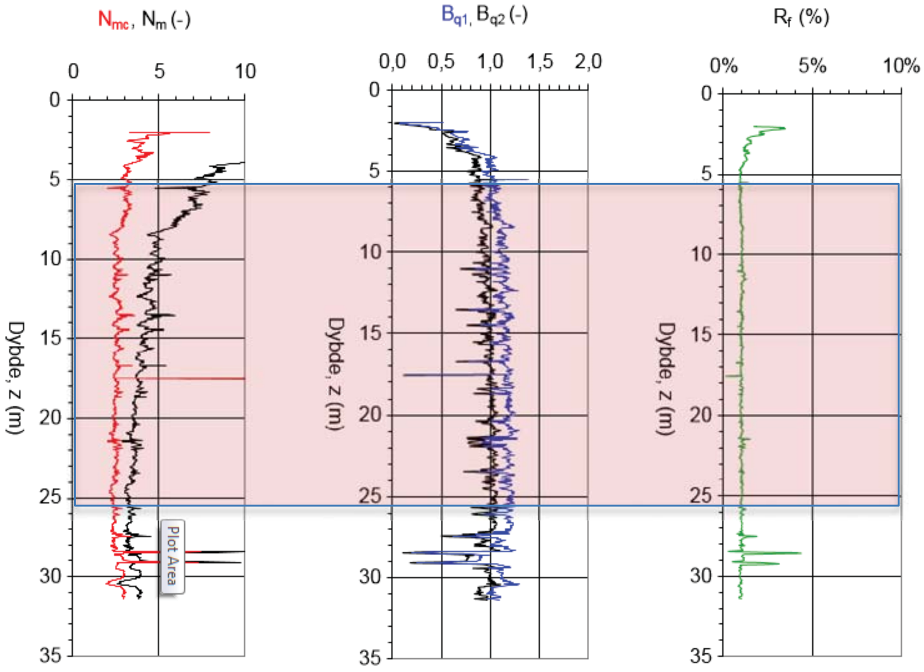


Figure B8.5 Fallan – CPTU profiles, N_m, B_q, R_f.

Figure B8.4 shows a CPTU-profile from the area. The profiles are characteristic for clays from this region, with a corrected cone resistance q_t increasing from about 500 kPa in the top of the soft layer to about 1800 kPa at 30 m depth. The sleeve friction is generally low, around 5-10 kPa in the quick clay layer. The pore pressure u_2 is relatively high, with values well above the hydrostatic distribution, corresponding to a pore pressure ratio of about B_q = 1,6-1,7. The results give the impression of a silty clay with silt lenses in the quick clay layer.

The National Geological Survey (NGU) carried out ERT-measurements along the proposed road line, see the ERT profile in Figure B8.6. The profile is 600 m long. In the north of the profile, a steep slope with a thin layer of soil deposits is encountered. The same conditions are found in the south-western part of the profile. Between these extremes, sediments with resistivity values from ca. 6 Ωm to 80 Ωm are detected, with the average resistivity being ±30 Ωm. Between profiles 370 and 450 some pockets of expected sand and gravel with higher resistivity (< 300 Ωm) are detected. Most likely, most of the soil deposits along the profile consists of leached clays.

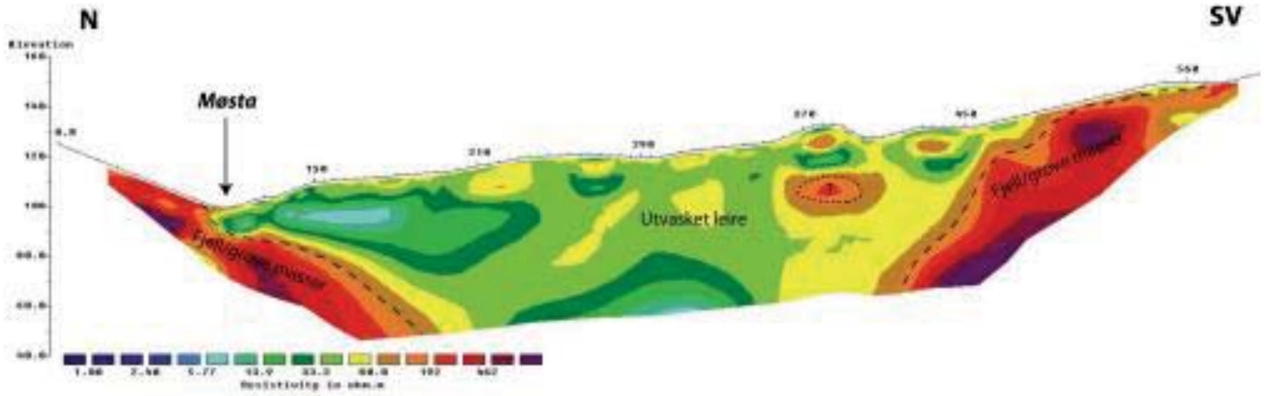


Figure B8.6. Fallan – ERT profile along planned road line.

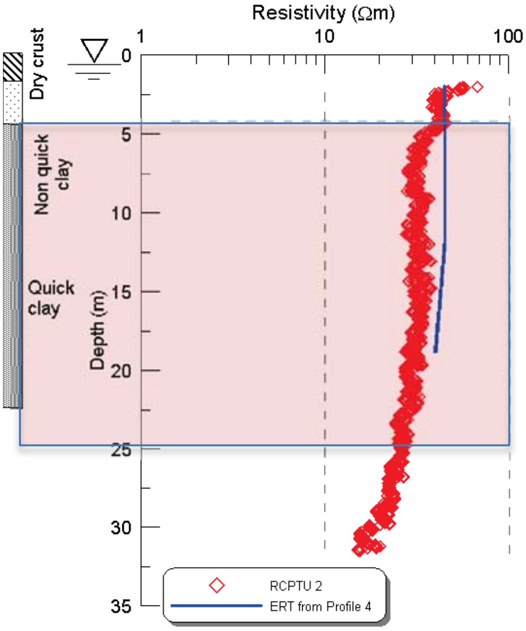


Figure B8.7. Fallan – comparison between ERT and R-CPTU measurements.

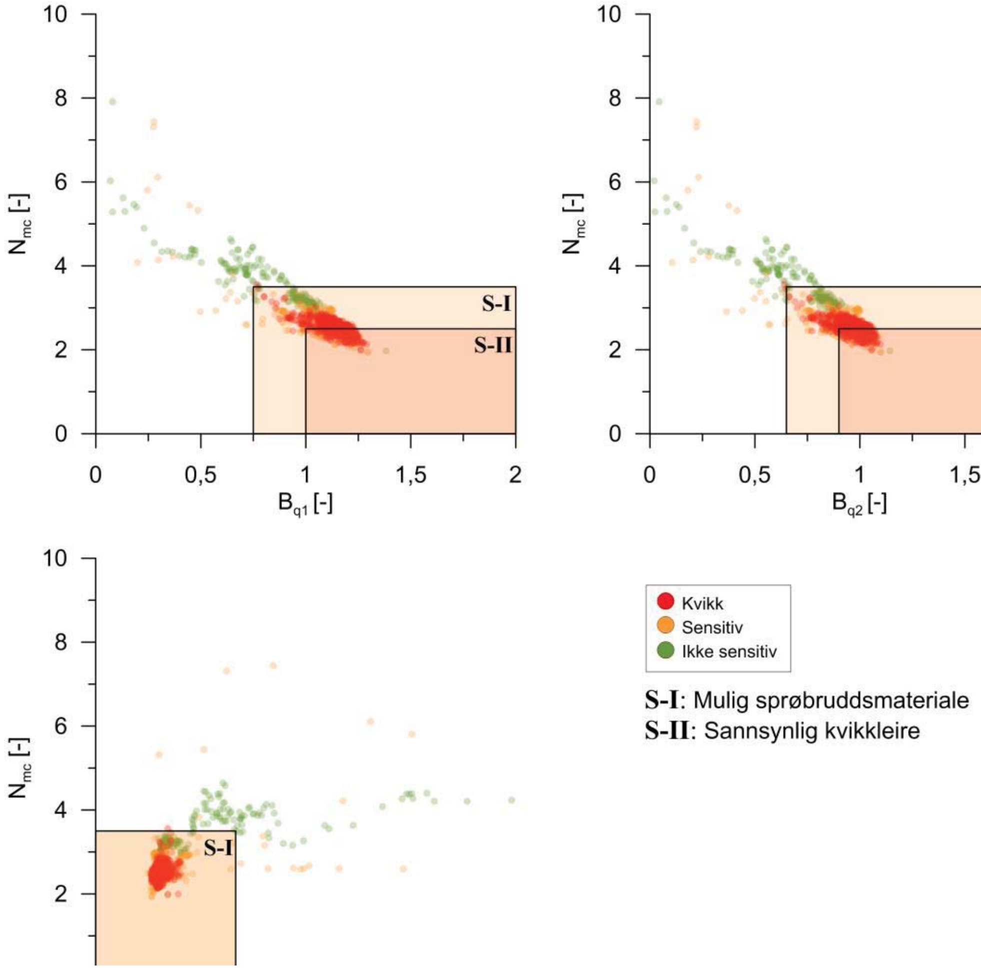


Figure B8.8. Fallan – New identification chart CPTU.

A comparison between R-CPTU and ERT data for Fallan is shown in Figure B8.7. The values are in good agreement, but the ERT-values are in average somewhat higher, similar to what was found at the other test sites.

Important references

Publications:

1. Sandven, R. et al (2013). *Geophysical and geotechnical investigations for a major highway in a quick clay area*. J-S. L'Heureux, m.fl. eds., Proceedings of the International Workshop on Landslides in Sensitive Clays (IWLSC) "From Geoscience to Risk Management". *University of Laval, Quebéc City, Canada. Springer, Dordrecht.*

Technical reports:

1. Multiconsult (2015). *Detection f quick clay by R-CPTU and electric field vane tests*. *Results from field study*.
   Multiconsult report no. 415559-2-RIG-RAP-003rev01.
   NIFS report no. R101-2015.

2. Multiconsult (2013). *New E6 Haga – Skjerdingstad. Data report site investigations.* Multiconsult report no. r414622. 2013.

Master theses:

1. Montafia, A. (2013). *Influence of physical properties of marine clays on electric resistivity and basic geotechnical parameters*. Master thesis, Department of Civil and Transport Engineering, NTNU, Trondheim.

Enclosure B9

Rein, Rissa

The Rissa test sites is located east of Rein church and west to the braquish lake Botn. The ground conditions are relatively complex, as shown in Figure B9.1, and the properties hence vary from borehole to borehole. The boreholes BH3 and BH 4 are emphasized, since results from laboratory tests on miniblock samples are available from these boreholes. The boreholes are also close to an ERT-profile through the area.

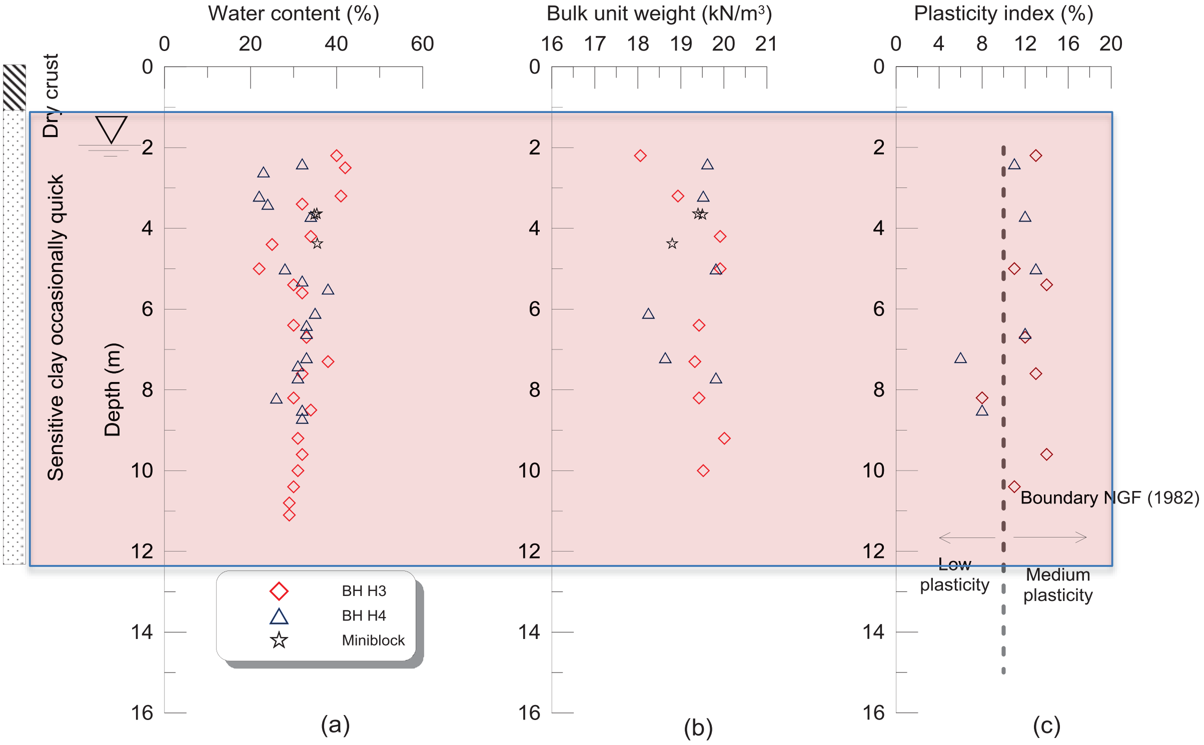


Figure B9.1. Rissa – basic index properties (BH3/BH4).

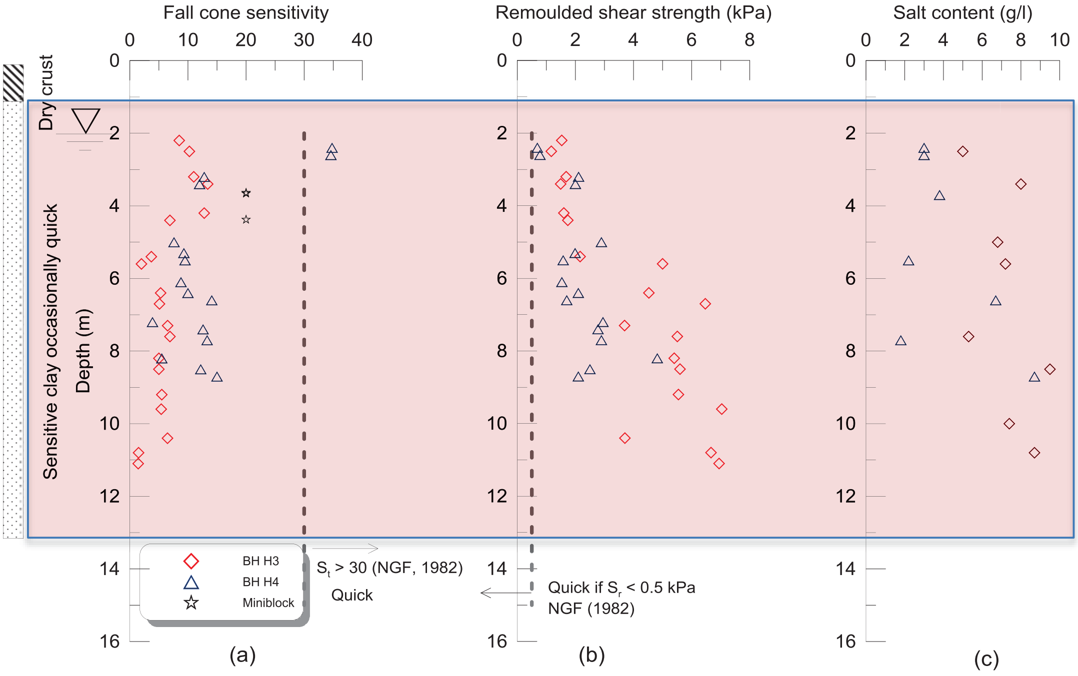


Figure B9.2. Rissa – sensitivity, remoulded shear strength and salt content (BH3/BH4).

The water content and density show larger variations compared to the other sites, but the average values are more or less similar. The plasticity is slightly higher, and the material is classified with medium to low plasticity. As shown in Figure B9.2, there exist no clearly defined quick clay layer since the quick clay is encountered in pockets and confined, discontinuous layers.

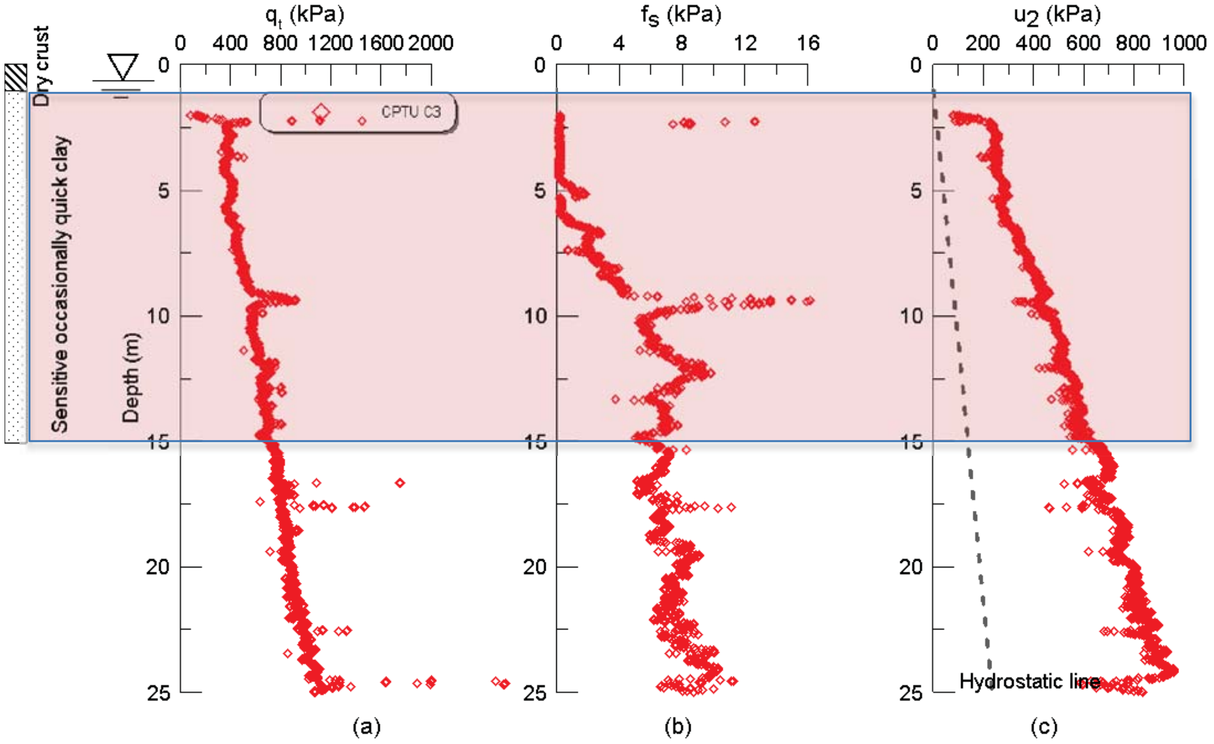


Figure B9.3. Rissa – CPTU profiles, q_t, f_s and u_2 (BH3/BH4).

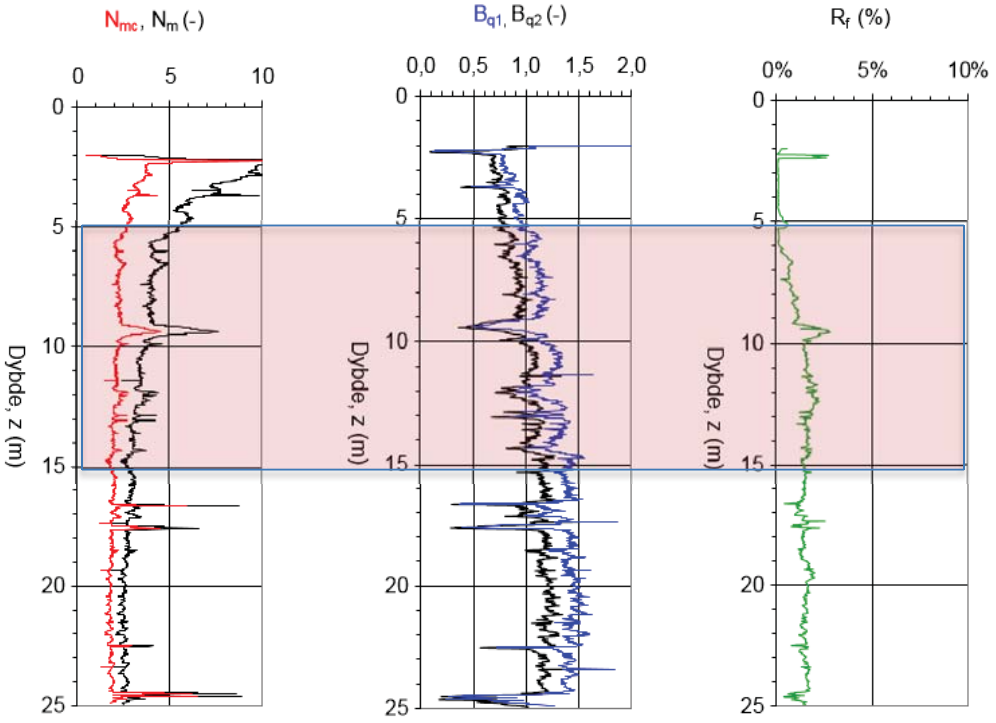
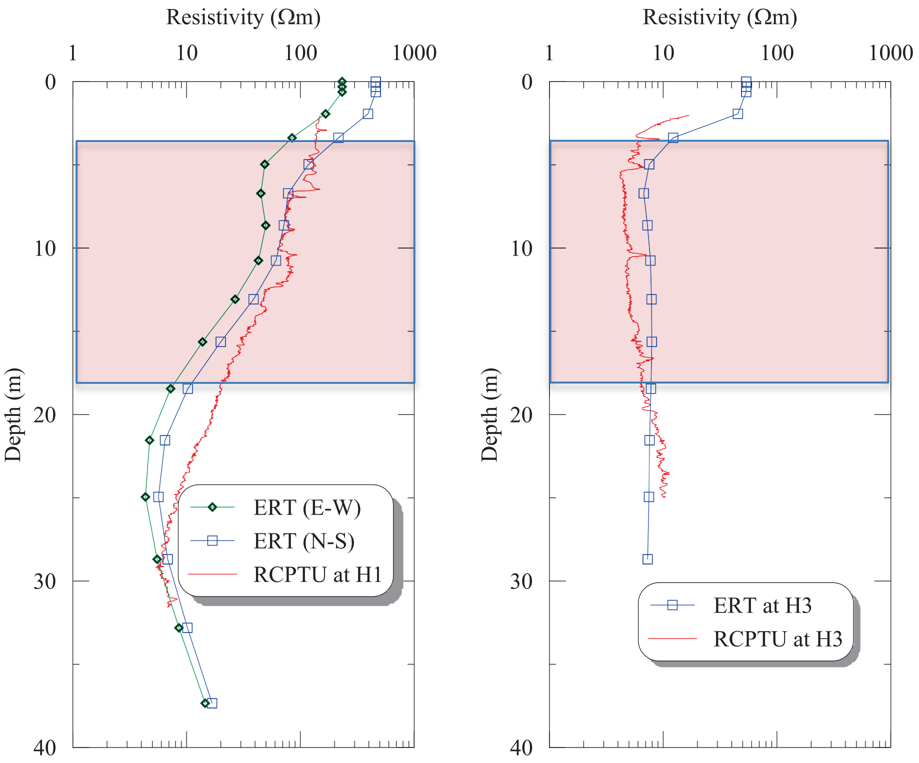


Figure B9.4. Rissa – CPTU profiles, N_m, B_q, R_f (BH3/BH4).

The remoulded shear strength shows a clear increase with depth. The salt content is relatively high compared to the other test sites, and plots in the range between 2 g/l to 10 g/l.



(a)

(b)

Figure B9.5. Rissa – comparison between ERT and R-CPTU measurements.

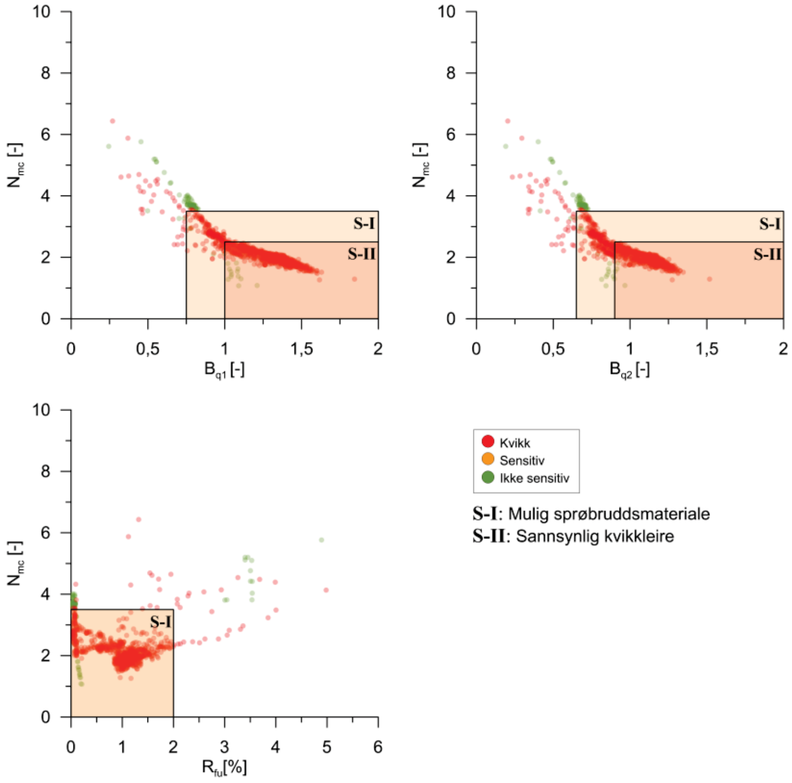


Figure B9.6. Rissa – new identification chart CPTU.

The CPTU profiles in Figure B9.3 show that both q_t and u_2 increase linearly with depth. The measured values are characteristic for clays from this district (Trøndelag). The sleeve friction increases down to about 10 m, below this level the values are approximately constant.

Despite the irregular ground conditions, the ERT and R-CPTU measurements agree well, see Figure B9.5. Data from borehole BH3 and BH4 are given, but borehole BH1 is also included in the figure, even if no laboratory data exist from this borehole.

Important references

Technical reports:

1. Statens vegvesen (NPRA) (2008). *RV 717 Sund – Bradden. Site investigations data report*. Statens vegvesen report no.2008/036571-1
2. Norwegian Geotechnical Institute (2009). *RV 717 Sund – Bradden. Site investigations data report.* NGI report no.20091264-00-36-R.
3. Norwegian Geotechnical Institute (2009). *RV 717 Sund – Bradden. Interpretation of site investigations, characteristical material parameters*. NGI report no.20091264-00-38-R.
4. Multiconsult (2011). *Interpretation report – previous site investigations.* Multiconsult report no. 414792-RIG-RAP-001.
5. Multiconsult (2011). *Interpretation report – new site investigations.* Multiconsult report no. 414792-RIG-RAP-002.

Master theses:

1. Aasland, R. (2010). *Mapping of quick clay by 2D resistivity and R-CPTU in Rissa (in Norwegian)*. Master thesis, Department of Civil Engineering and Transport, NTNU, Trondheim.
2. Kåsin, K. (2010). *CPTU in quick clay in Rissa (in Norwegian).* Master thesis, Department of Civil Engineering and Transport, NTNU, Trondheim.
3. Kornbrekke, H.A. (2012). *Stability evaluation of Rissa clay slopes based on block samples*. Master thesis, Department of Civil Engineering and Transport, NTNU, Trondheim.

Enclosure B10

Nidarvoll

The Nidarvoll test site is uncommon compared to the other Trondheim sites since it consists of two distinct clay layers. The upper clay layer has medium plasticity, relatively high water content (w =44,8 %) and relatively low density (ρ_{avg} = 1,80 g/cm^3). The lower layer is quick, and has lower average water content (w =30,7 %), higher density (ρ_{avg} = 1,95 g/cm^3) and has very low plasticity, see the Figures B10.1 and B10.2. A dense layer is encountered at about 25 m depth.

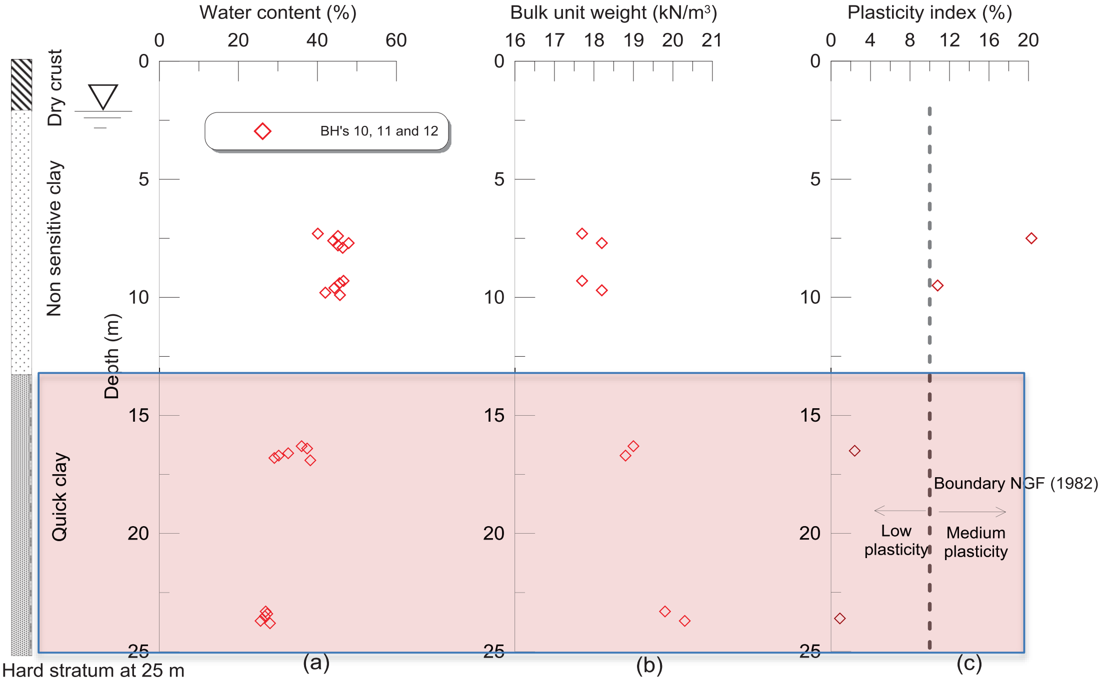


Figure B10.1. Nidarvoll – basic index properties.

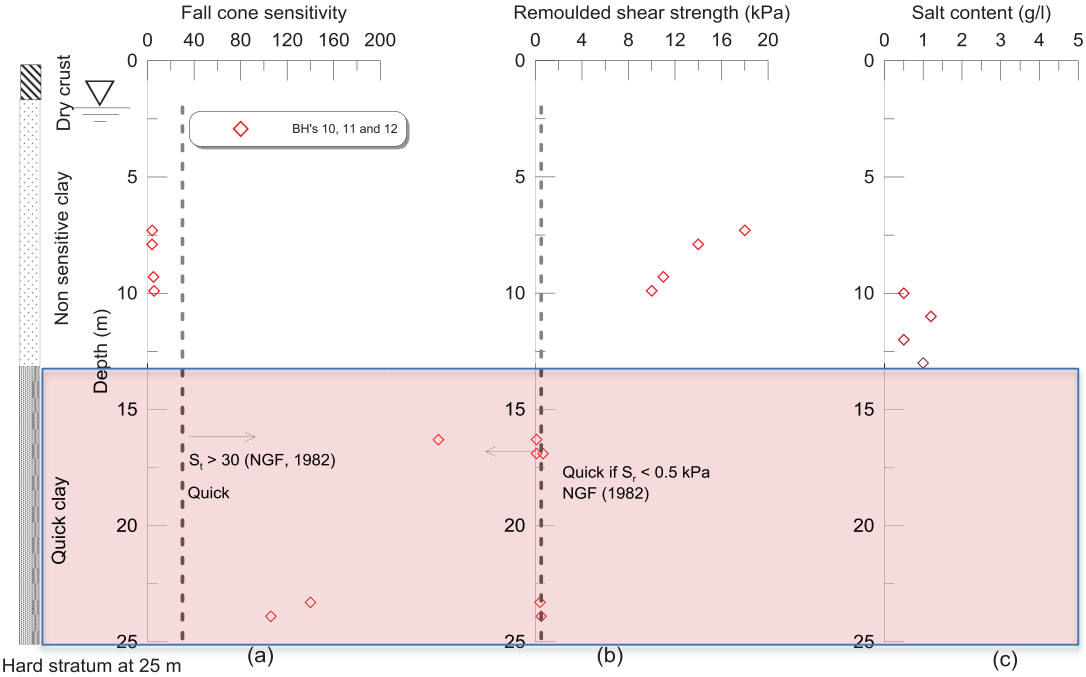


Figure B10.2. Nidarvoll – sensitivity, remoulded shear strength and salt content.

The salt content for the Nidarvoll site is relatively low, see Figure B10.2.

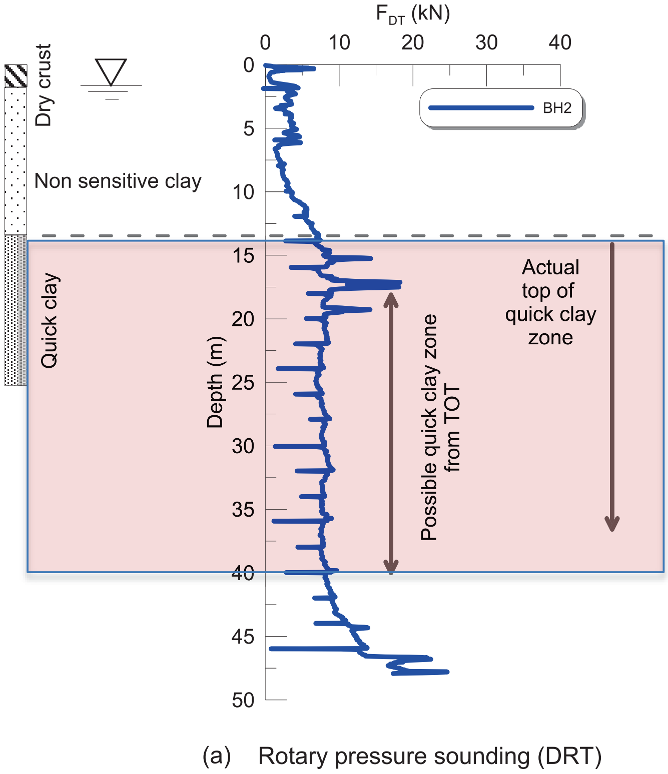


Figure B10.3. Nidarvoll – rotary pressure sounding profile.

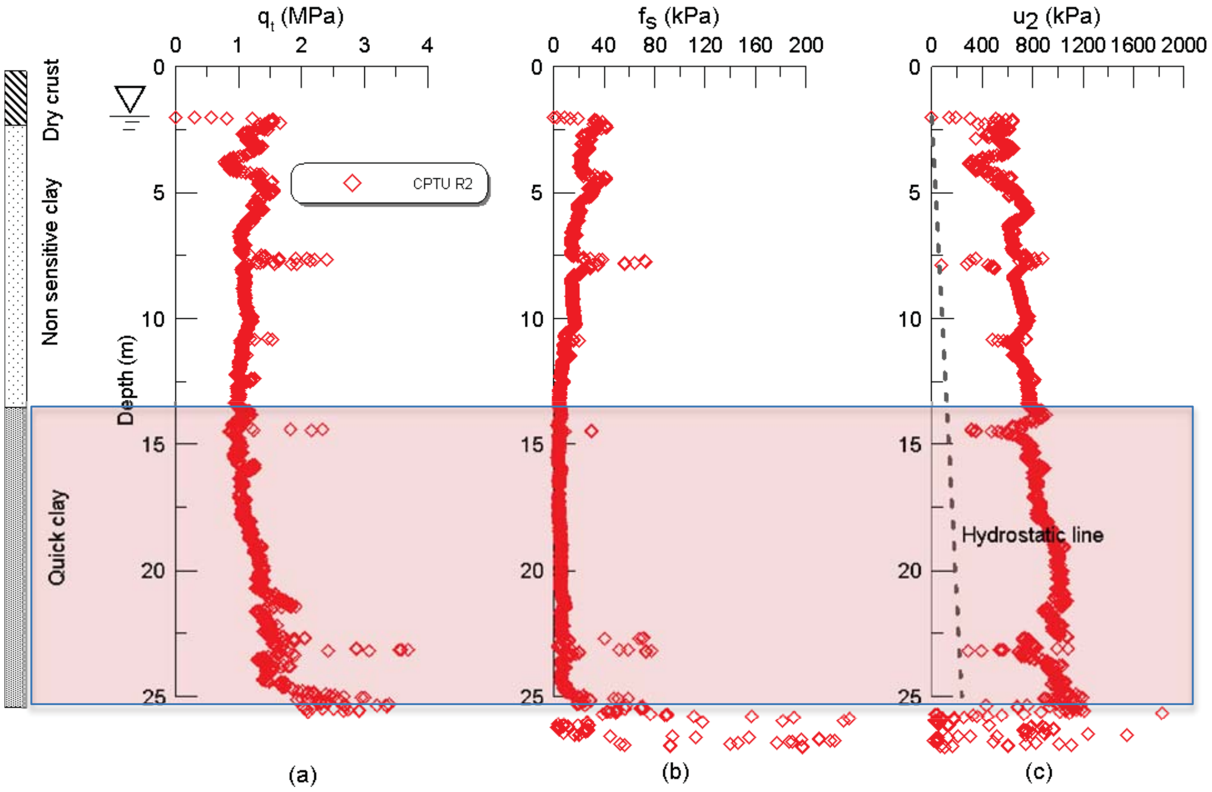


Figure B10.4. Nidarvoll – CPTU data, q_t, f_s and u_2.

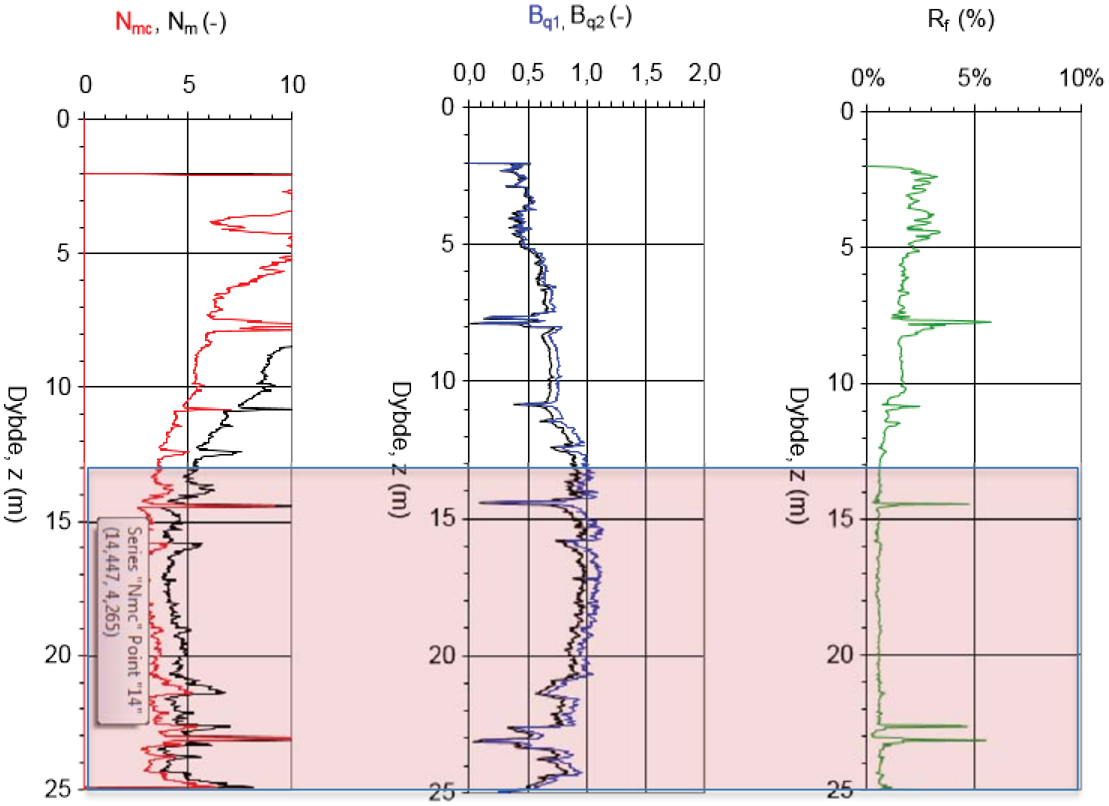


Figure B10.5. Nidarvoll – CPTU data, N_m, B_q, R_f.

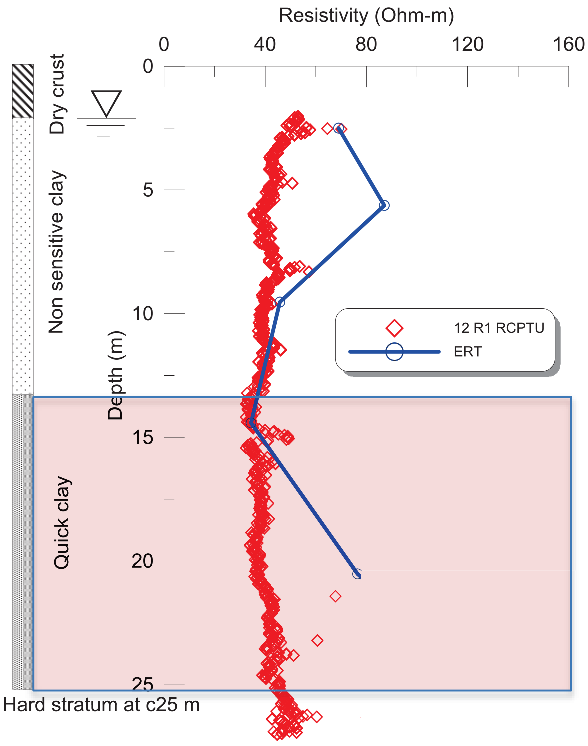


Figure B10.6. Nidarvoll – comparison between ERT and R-CPTU measurements.

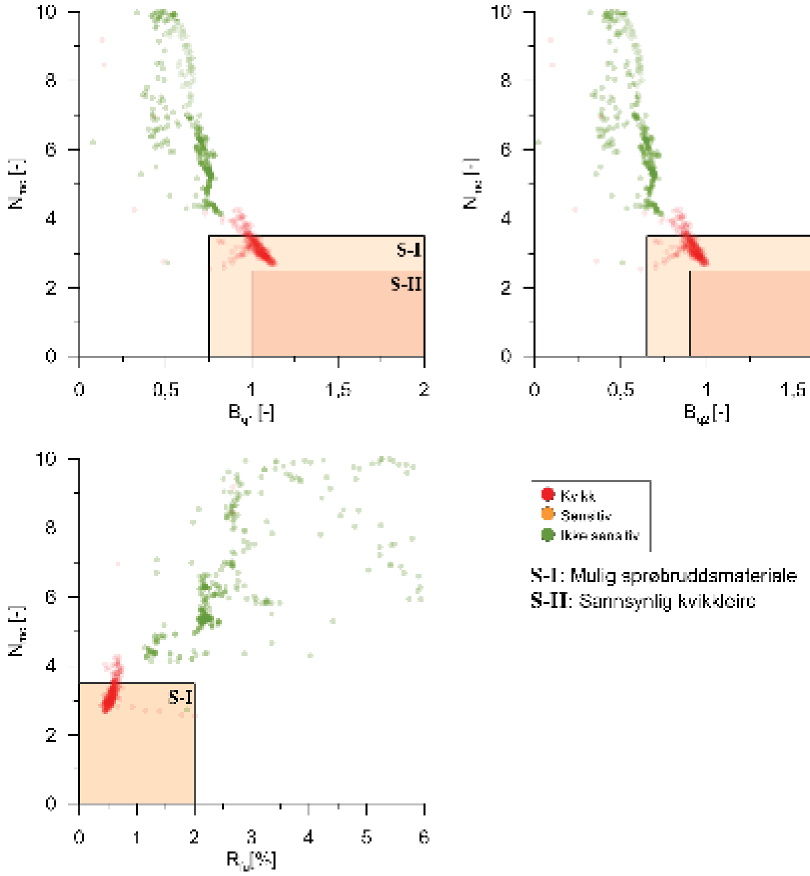


Figure B10.7. Nidarvoll – new identification chart CPTU.

CPTU results from Nidarvoll are shown in Figure B10.4. The results are somewhat different from the other Trondheim clays since the corrected cone resistance (q_t) is higher, it does not show an increase by depth and have also some indications of silt- and sand layers in the profiles. The sleeve friction (f_s) is generally low, but generally higher in the upper, non-sensitive layer. The pore pressure values (u_2) are as usual much higher than the hydrostatic value, but is reduced near the silt- and sand layers.

A comparison between ERT and R-CPTU measurements for Nidarvoll is shown in Figure B10.6. In the upper layer, the ERT-values are somewhat higher compared to the R-CPTU values. In the lower layer and in the upper part of the quick clay, the agreement between the values is very good. In the lower part of the quick clay, the ERT-values are again higher. It is likely that the measurements in this part are influenced by the deeper, dense layer at about 25 m depth (assumed morainic soils).

Important references

Master theses:

1. Hundal, E. (2014). *CPTU with measured total sounding resistance, New possibilities for detection of quick clay? (In Norwegian),* Master thesis, Department of Civil Engineering and Transport, NTNU, Trondheim.

Enclosure B11

Rødde

The test site Rødde is located at Melhus in the valley Gauldalen, about 15 km south of Trondheim. The area consists of thick deposits of marine clays and silts from the last deglaciation. The terrain is typical for Norwegian clay areas below the marine limit (MG), with frequent traces and scars after slides and excessive ravination. The area is interesting due to a large silt content, and this test site is hence slightly different compared to the other test sites.

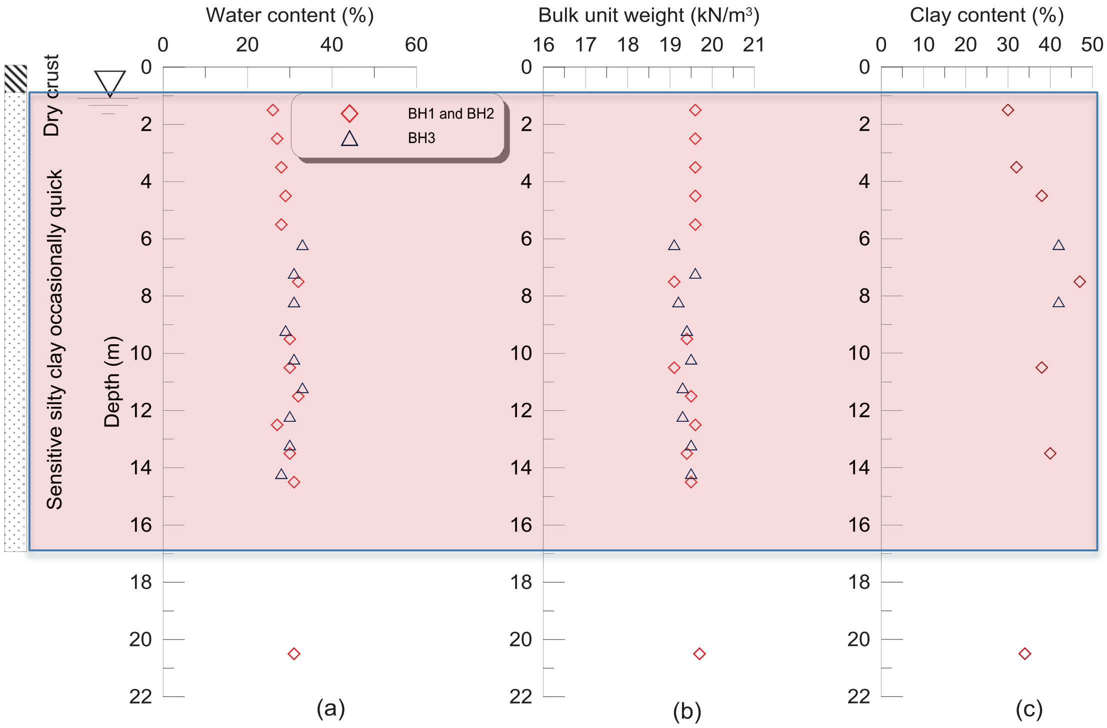


Figure B11.1. Rødde – basic index properties.

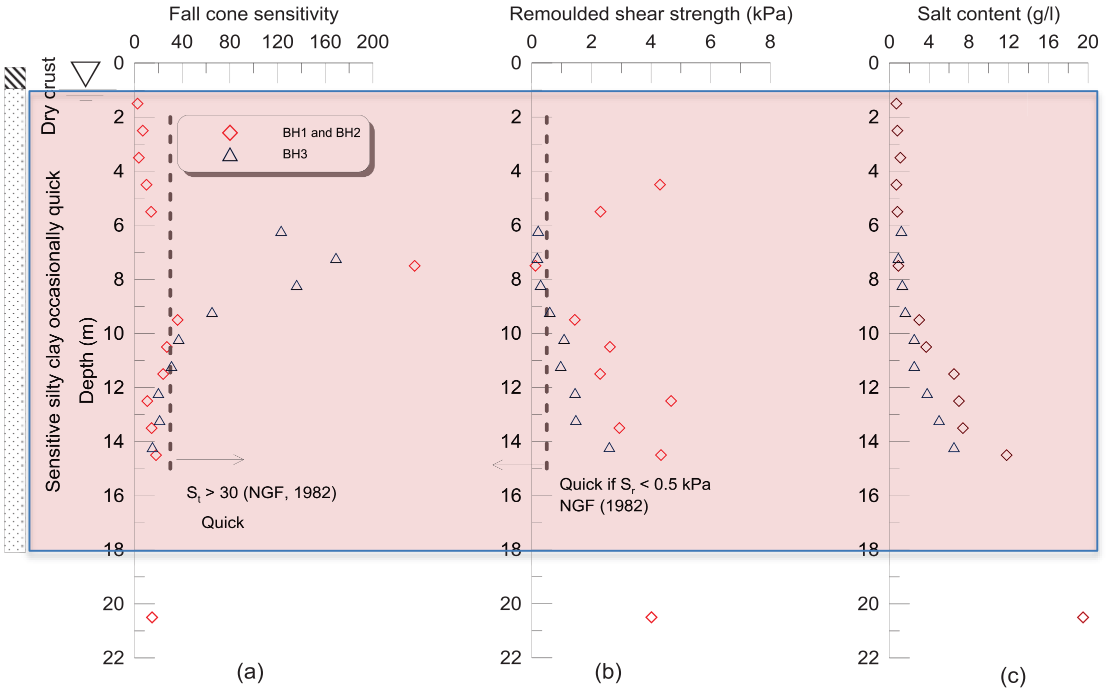


Figure B11.2. Rødde – sensitivity, remoulded shear strength and salt content.

The basic index properties are shown in Figure B11.1. The average water content is ca. 29,9 %, which is low compared to the other test sites. Accordingly, the average density is 1,94 g/cm^3, which is relatively high. The average clay content is 38,1 %. With respect to content of quick clay, the conditions are relatively complex, as shown in Figure B11.2. A quick clay layer appears between ca. 6,0 m and 9,5 m in some boreholes. The remoulded shear strength and the silt content seem to increase with depth. Figure B11.3 shows a typical CPTU-profile from the area.

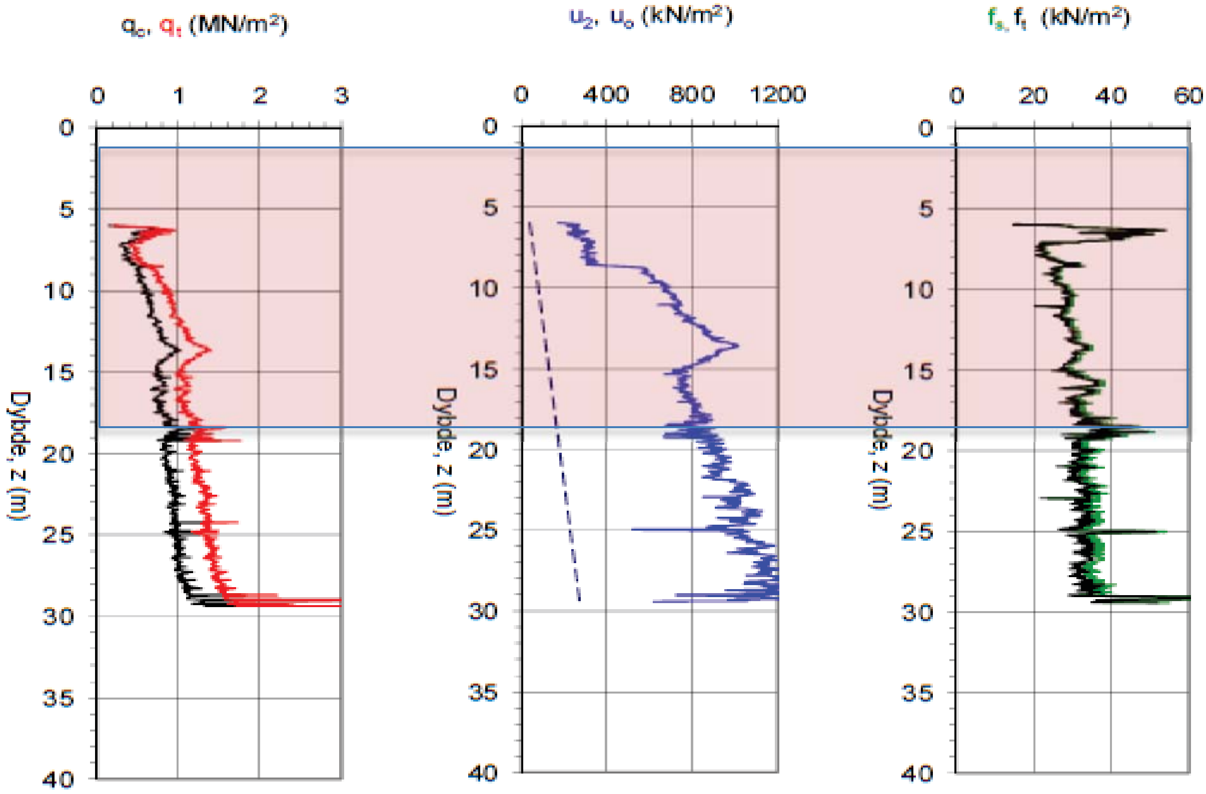
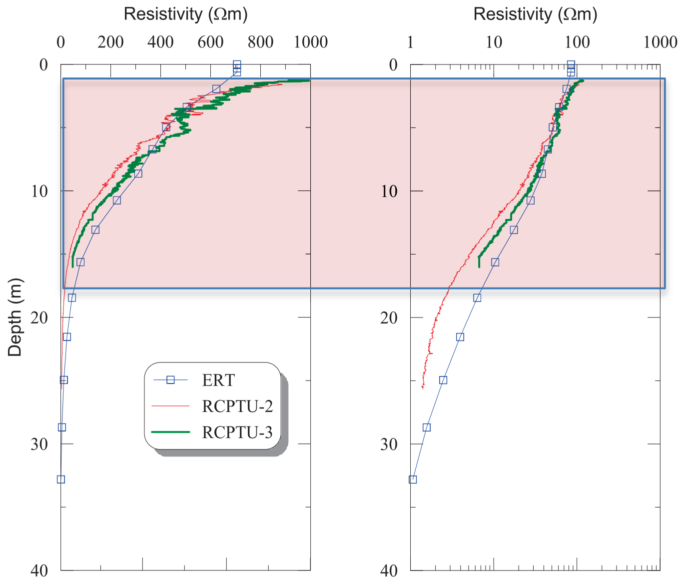


Figure B11.3. Rødde – CPTU profiles, q_t, f_s and u_2.



(a) (b)

Figure B11.4. Rødde – comparison between ERT and R-CPTU measurements.

Data from ERT and R-CPTU tests at Rødde are compared in Figure B11.4, with the resistivity in both logarithmic and linear scales. The results show very good agreement between the two methods.

Important references

Technical reports:

1. Multiconsult (2010). *Quick clay mapping in Melhus and Trondheim. Site investigations – data report.* Multiconsult report no.r413809-1, February 2010.
2. Norwegian Geotechnical Institute (2009). *Zone Litj-Ler, Sørnypan, Asgarden, Stokkaunet and Rødde in Melhus. Quick clay mapping and stability evaluations (in Norwegian).* NGI report no.20091127-00-73-R.

Master theses:

1. Ottesen, H.B. (2009). *CPTU with resistivity measurements (In Norwegian).* Master thesis, Department of Civil Engineering and Transport, NTNU, Trondheim.

Enclosure B12

Ranheim west (Borehole E5)

The Ranheim west test site shows far more complicated ground conditions compared to the other test sites. The area partly consists of shoreline deposits in the central and northern parts of the test site, with thick marine deposits in the south.

The following observations are made with respect to the basic index properties for the soil:

- Materials from the southern area has lower water content, higher density and higher undrained shear strength than corresponding materials from the north. This is possibly the opposite from what can be expected
- Even if the values from the northern part are higher, the soils have lower water content than what commonly is the case for Norwegian clays (average ≈ 26%). The soils have also relatively high density (in average ≈ 2,02 g/cm^3).
- Quick clay is only identified in one borehole (E5 on the northern part of the test site).

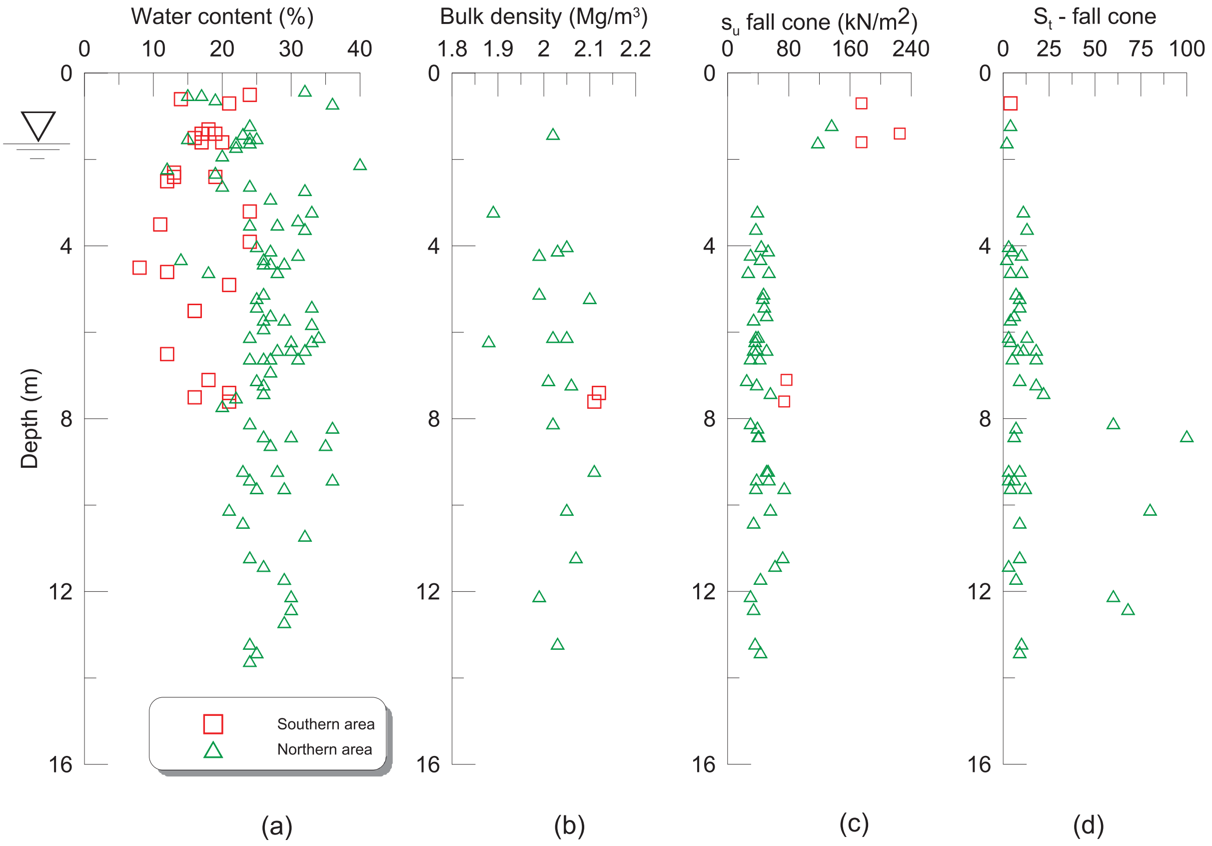
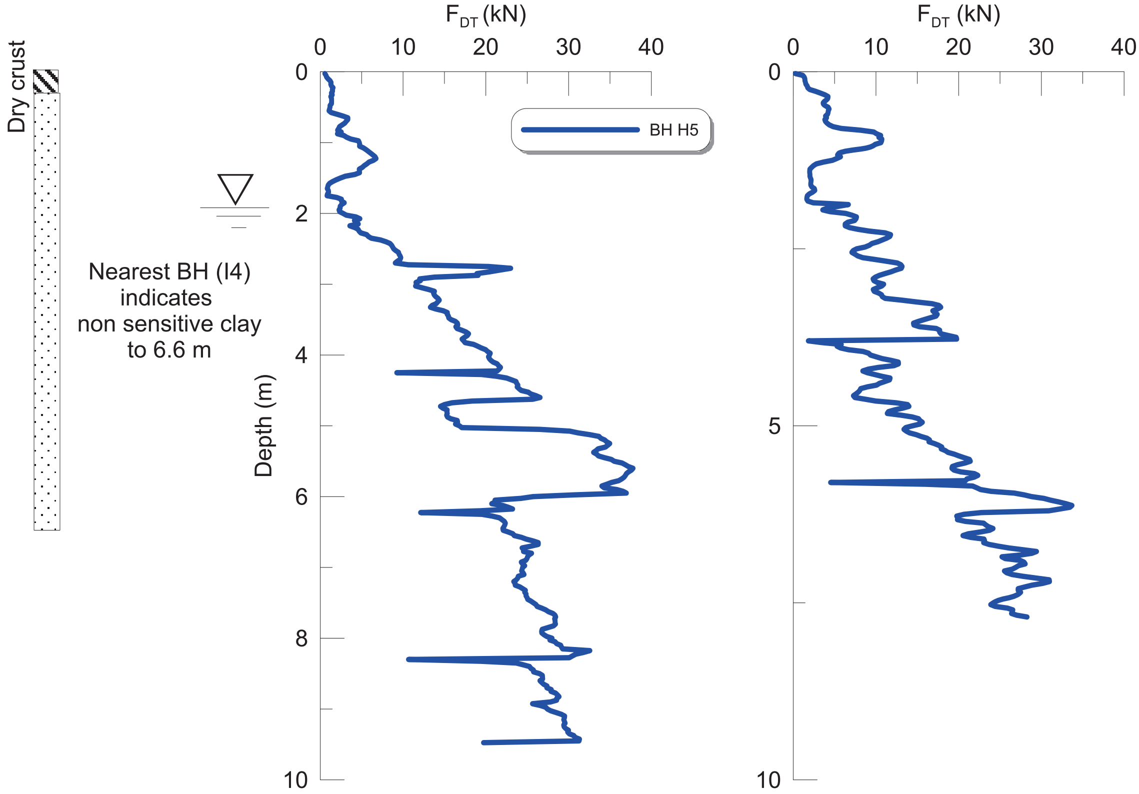


Figure B12.1. Ranheim west – basic index properties (areas south and north).

Figure B12.2 shows a comparison between DRT- and TOT sounding profiles from the upper 10 m of the profile. A comparison between ERT and R-CPTU data is shown in Figure B12.4. The two types of measurements show almost similar test results. The relatively high resistivity values is probably caused by a large silt- and sand content in the deposits.



(a) Rotary pressure sounding (DRT)

(b) Total sounding (TOT)

Figure B12.2. Ranheim west – comparison between shallow rotary pressure- and total sounding profiles without detection of quick clay layers (0-10 m) (borehole E5).

Figur B12.3 viser et typisk CPTU-profil fra området.

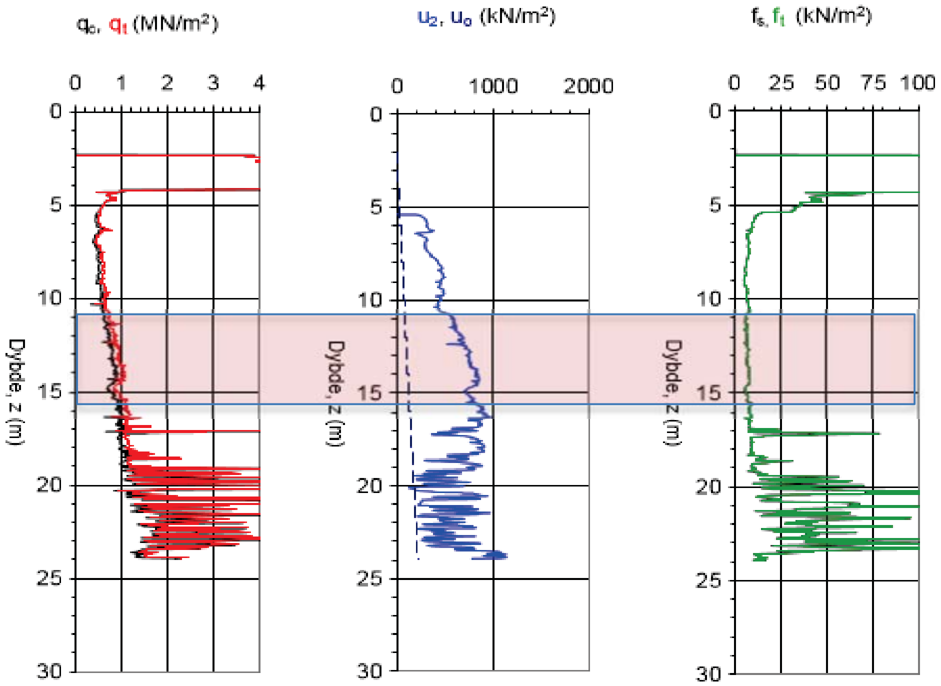


Figure B12.3 Ranheim west – CPTU profiles, q_t, f_s and u_2 (borehole E5).

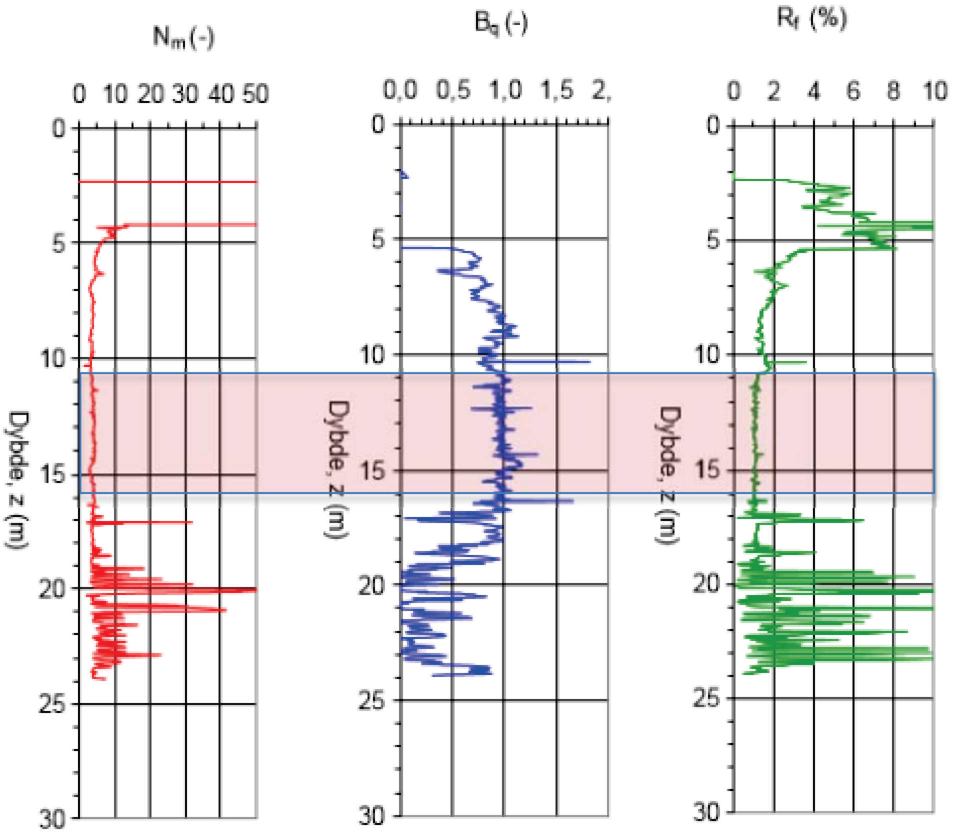


Figure B12.4 Ranheim west – CPTU profiles, N_m, B_q, R_f (borehole E5).

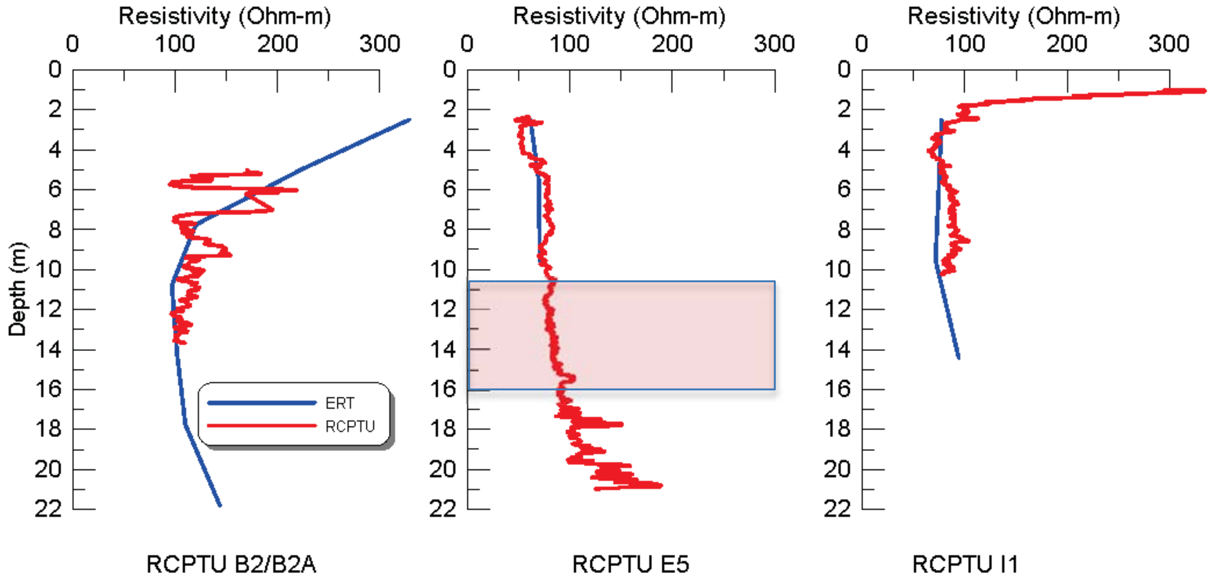


Figure B12.5. Ranheim west – comparison between ERT and R-CPTU measurements.
<u>Remarks:</u> Borehole B2/B2A is located in the southern part of the area, whereas borehole E5 is located in the south-eastern part. It shows some content of quick clay between 11-16 m. Borehole I1 is located in the northern part of the area.

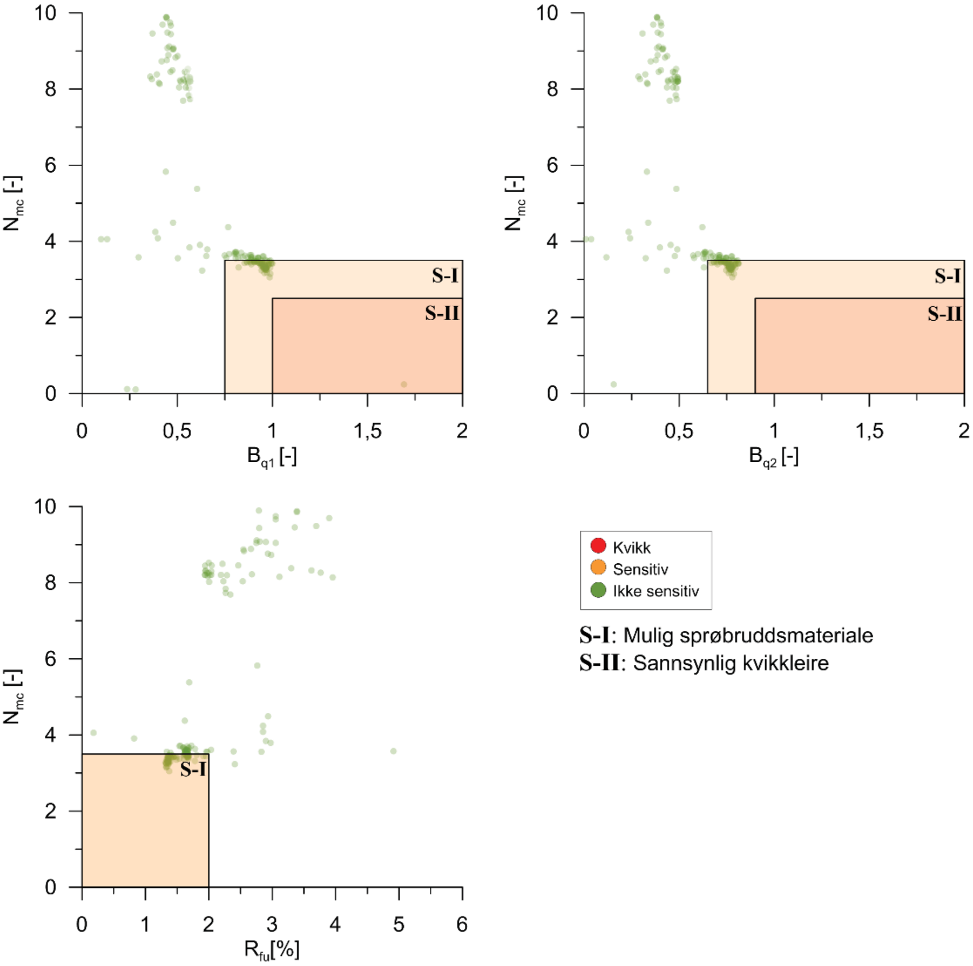


Figure B12.6. Ranheim west – new identification chart CPTU. (Remarks: Possible quick clay or brittle materials are not verified by laboratory tests for this profile).

Important references

Technical reports:

1. Multiconsult (2014). *Ranheim Eiendomsutvikling AS. Geotechnical evaluation for regulation plan.* Multiconsult report no.416235-RIG-RAP-002.

Master theses:

1. Hundal, E. (2014). *CPTU with measured total sounding resistance, New possibilities for detection of quick clay? (In Norwegian).* Master thesis, Department of Civil Engineering and Transport, NTNU, Trondheim.

Does not contain quick clay

Enclosure B13
Hommelvik seaside

The test site at Hommelvik seaside has a completely different geological history than the other test sites. The ground conditions consist of a complex composition of delta deposits, and contains shifting layers of clay, silt and sand. Land reclamation has also been carried out in the area. The area is composed of layers with coarse material of varying thickness over a silty clay, see Figure B13.1. The silty clay has an average water content w_{avg} of about 25% and a density ρ_{avg} of 2,10 g/cm^3.

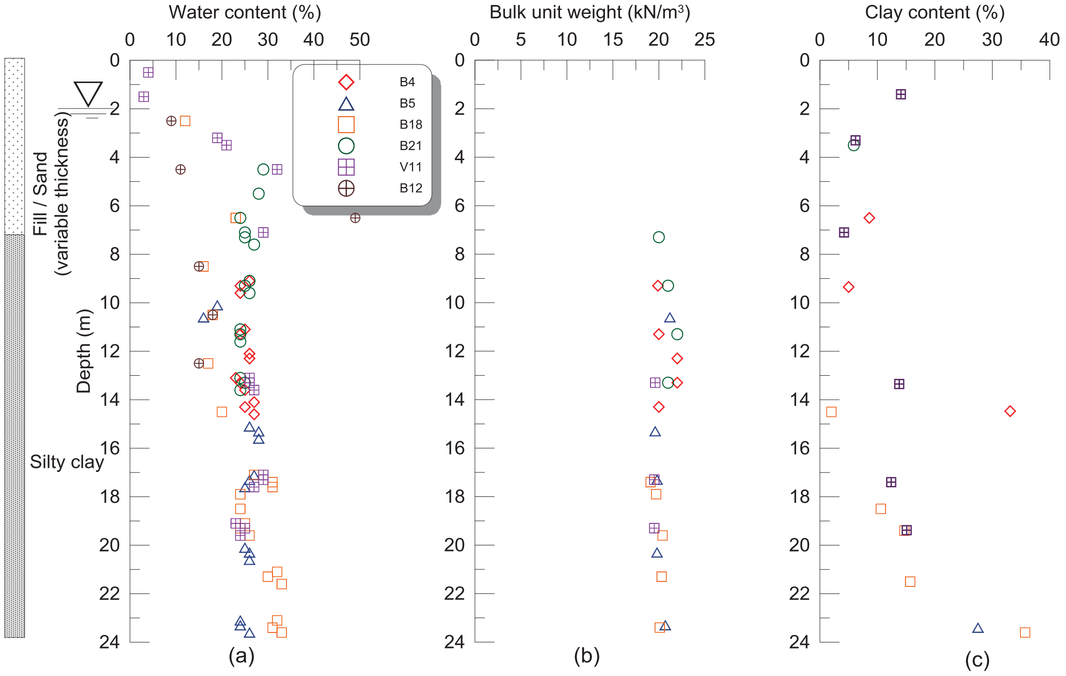


Figure B13.1. Hommelvik seaside – basic index properties.

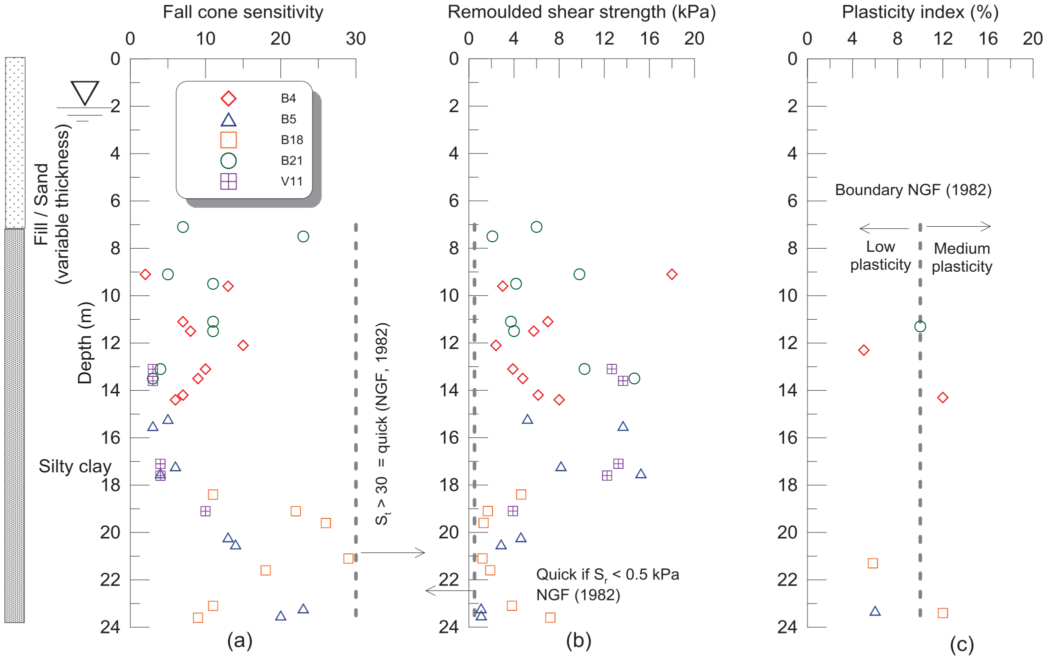


Figure B13.2. Hommelvik seaside – sensitivity, remoulded shear strength and plasticity.

The clay has low to medium sensitivity and has low to medium plasticity, see Figure B13.2.

The CPTU results in Figure B13.3 confirms this stratification. Coarse materials, with relatively high q_t and f_s values, are situated above more fine-grained silts and clays. These layers are easily detected by the difference in u_2 and u_0 values.

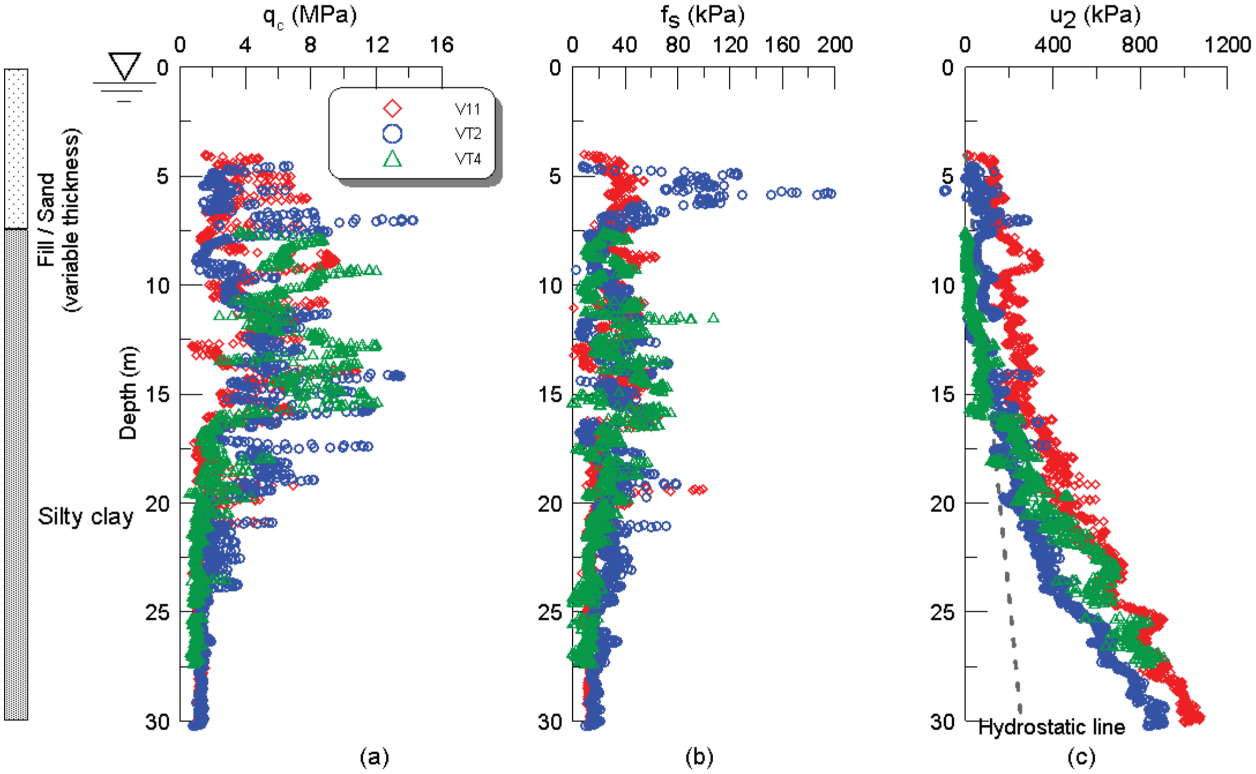


Figure B13.3. Hommelvik seaside – CPTU profiles, q_t, f_s and u_2 (boreholes V11, VT2, VT4).

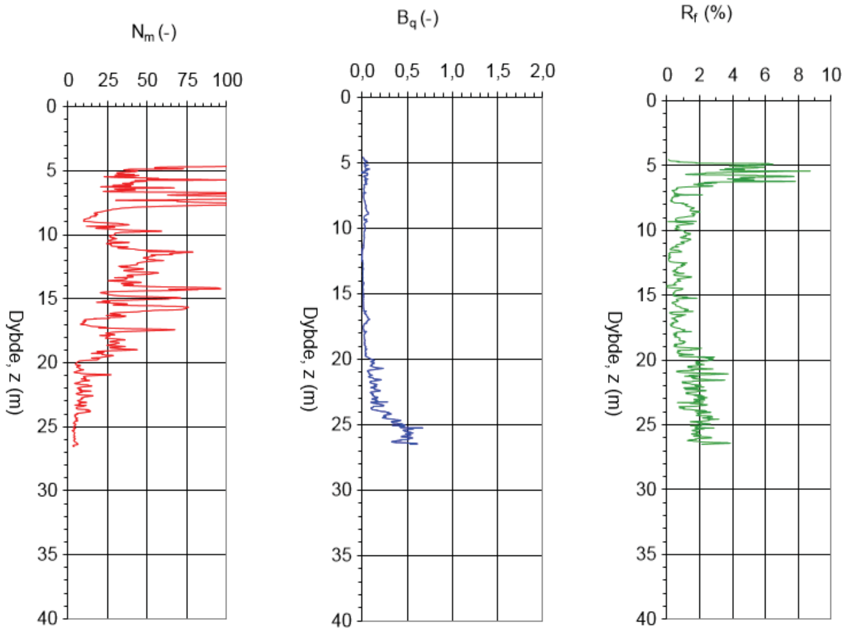


Figure B13.4. Hommelvik seaside – CPTU profiles, N_m, B_q, R_f (borehole VT2).

A comparison between ERT and R-CPTU results from the area is shown in Figure B13.5. The results confirms the location of a coarse layer with high resistivity above a finer layer with very low resistivity. The thickness of the upper layer show large variations in thickness over the area. The ERT-values are generally higher than those obtained by R-CPTU in both layers.

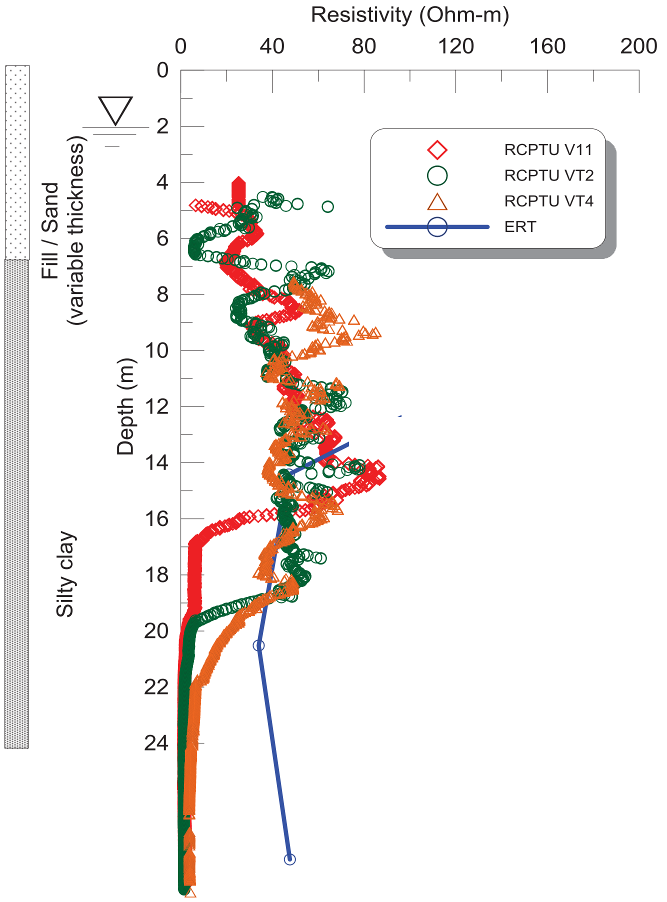


Figure B13.5. Hommelvik seaside – comparison between ERT and R-CPTU measurements.
Remarks: *R-CPTU v/I1 is located close to the ERT profile.*

Important references

Technical reports:

1. Norwegian Geotechnical Institute (2013). *Hommelvik seaside. Geotechnical data report (In Norwegian)*. NGI report no.20130532-02-R.
2. Norwegian Geotechnical Institute NGI) (2011). *Hommelvik seaside AS. Run-out distance for slide debris from a possible quick clay slide in the area Lia-Skjeldbreda (In Norwegian).* NGI report no. 20091622-00-28-TN
3. Rambøll (2014). *Malvik kommune, Lia Hommelvik, quick clay area.* Rambøll report no. 1350004692-Geo-R01.

Enclosure B14
Summary of all resistivity measurements with R-CPTU

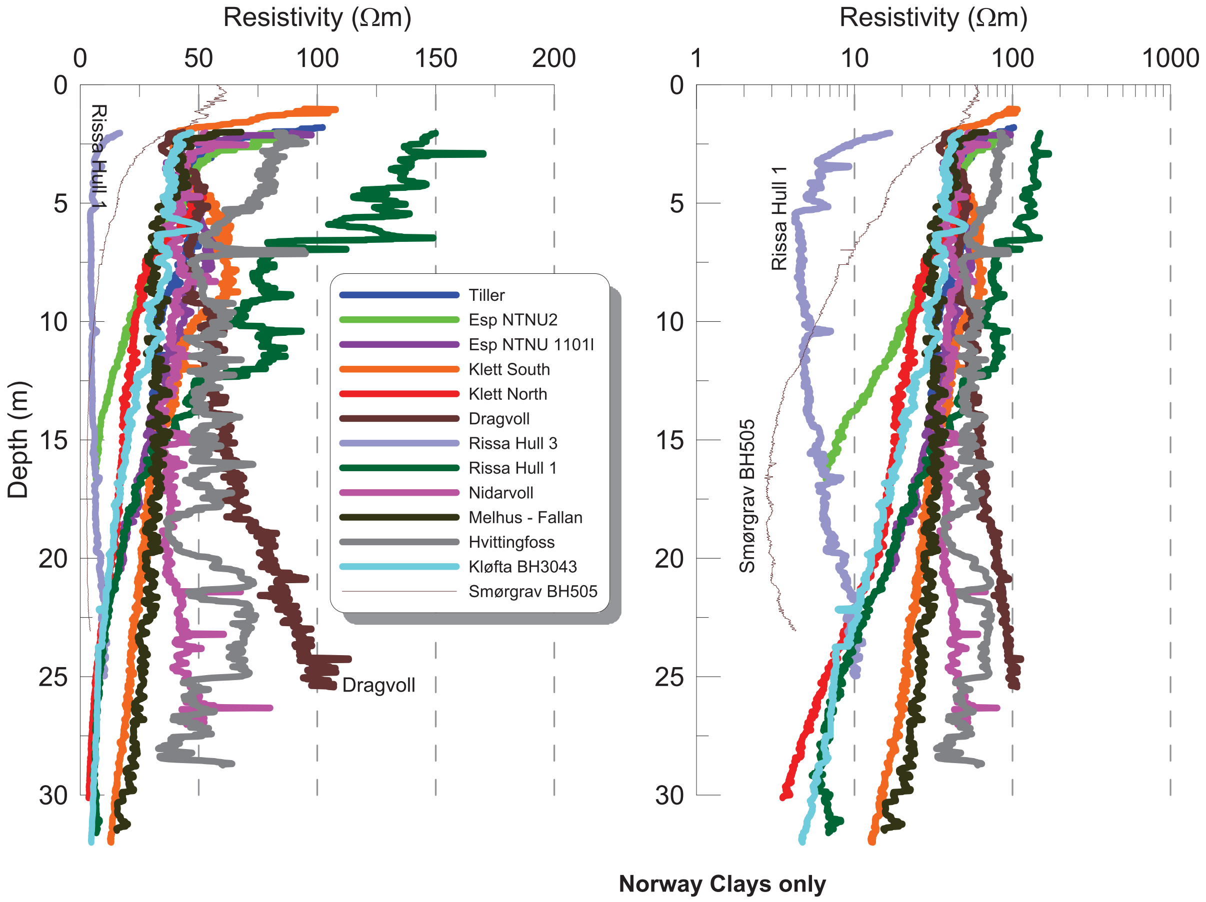


Figure B14.1. Summary of all resistivity measurements with R-CPTU.

ENCLOSURE C

Examples of site investigations

with combined use of geophysical and geotechnical methods

Example C1: Site investigations along road lines and terrain corridors

Project: New E16 Kløfta, section Nybakk – Slomarka (NGI), Norway
(NGI report 20130058-01-R, Anschütz et al 2015).

Example C2: Site investigations for large areas

Project: Evaluation of the stability conditions along Göta river
(GÄU report 30 Løfroth et al, Linköping, Sweden 2011)

Example C1: Site investigation along road lines and terrain corridors

Project: New E16 Kløfta – Kongsvinger, section Nybakk – Slomarka.
Combination of AEM, geotechnical borings and ERT as effective ground investigation
(NGI report no.20130058-01-R, Anschütz et al, 2015).

A section of 32 km new highway between Nybakk and Slomarka, around 50 km northeast of Oslo, is the last remaining part of the new E16 between Kløfta and Kongsvinger to be developed. As a part of the geotechnical evaluation, it was decided to supplement the boring program for the site investigation with an AEM-investigation (Airborne Electromagnetic Measurements). The purpose with the investigation was to map the depths to bedrock and possible quick clay deposits.

In geotechnical investigations in Norway, seismic refraction is the most well-known geophysical method, but resistivity measurements have become increasingly popular in recent years. 2D resistivity measurements on the surface (ERT) is a well-known method, but is relatively expensive for mapping of larger areas. The E16-project represented a unique possibility to test if one of the best AEM-systems in the world could provide sufficient depth resolution with measurements from helicopter. The helicopter flies along a line that shall be evaluated for geotechnical and constructional purposes.

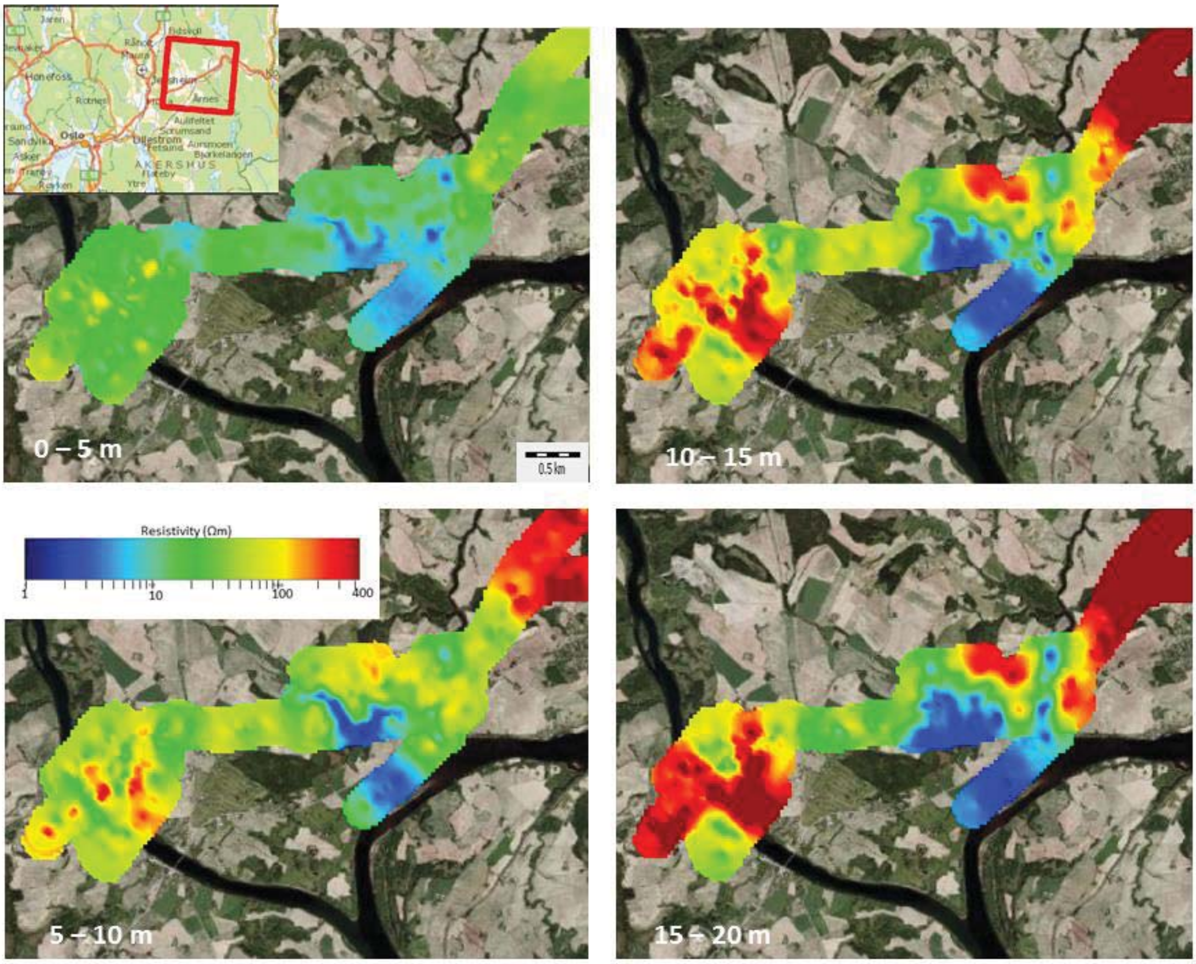


Figure C1.1 Resistivity map in 4 different depth intervals (0-5, 5-10, 10-15 and 15-20 m below the terrain surface) showing the heterogenity of the soil layers near the rivers Vorma and Uåa.

Airborne electromagnetic measurements (AEM or AEM – surveys) is a well-known geophysical method in the mining industry, used for tracing mineral deposits. In the last 15 years, the AEM-method has been further developed to enable mapping with high depth resolutions and accuracy. This accuracy is necessary for mapping of soil layers for hydrogeological and geotechnical applications.

In the end of January 2013, altogether 178 line-kilometers were flown by a SkyTEM 304 AEM-system mounted on a helicopter, along the planned road line at E16. Three lines were measured with an internal distance of 25 m. Additional shorter stretches were measured near the rivers Vorma (15 lines) and Uåa (9 lines), with an internal distance of 125 m. In this area, deposits of quick clays were expected, and further lines were necessary. The raw data were processed and inverted using the "Aarhus Workbench" software package, which is based on "Spatially constrained inversion" (SCI) to give resistivity values along the profile lines and by depth (see Figure C1.1). During processing of the results, data close to power lines and other noise sources were deleted, and the data was also corrected for varying flying heights and effect of tree tops.

An integrated ground model, consisting of 3D-models of electric resistivity and data from several hundred boreholes, confirmed the mapping of the bedrock by AEM. In this way, one may achieve cost savings, if the AEM-data are collected and analyzed before planning of the ground investigation program. In addition, AEM also have a potential in detection of sensitive clay, but this approach depends on measurements on the ground to obtain sufficient resolution. To obtain this, ERT data were collected along a profile with known deposits of sensitive clay. Comparison between AEM and ERT data shows very good agreement between the measurements.

Figure 2.12 in the main text of this report, shows an AEM profile along the same road corridor. The yellow and red colours indicate high resistivity, and hence represents the bedrock surface itself or a transition zone to bedrock. Blue colour corresponds to possible marine clays, whereas the green colour represents resistivity intervals for leached clay (possible quick clay). Since other materials can have the same resistivity, it does not mean that all green-coloured areas in the profiles necessarily contain quick clay/sensitive clay. To be able to compare the AEM-results with borehole data, the latter were superimposed on the presentation of AEM data. By comparing the results, one may identify areas with large possibility of quick clay deposits.

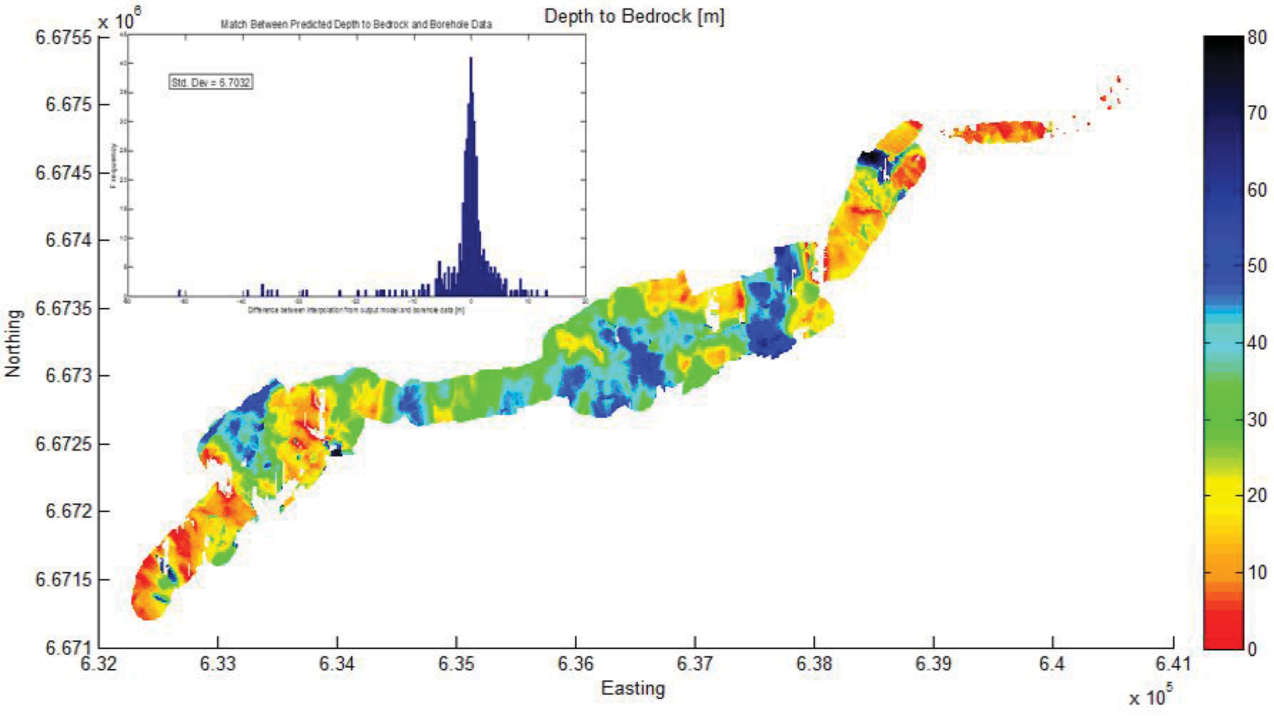


Figure C1.2 Map of AEM depth to rock, based on a variable threshold value and comparison of AEM-results, and results from borings (the histogram shows a standard deviation between borings and AEM on 6 m).

Figure 2.12 in the report shows that the depth to bedrock varies considerably in the investigated area. In some sub-areas, the variation in depth to bedrock is however much less. Based on these data, one may reduce supplementary borings where the depth to bedrock is not critical, and thereby save costs. The bedrock topography for the whole area was finally determined by a comparison between the AEM models and results from borings. In Figure 2.12, it is evident that the limit value for the resistivity in soils and rocks is variable. To find a final elevation for the bedrock surface, a data base with resistivity limit values for all borings were established. This database was utilized to produce an integrated bedrock surface for the whole area (see Figure C1.2).

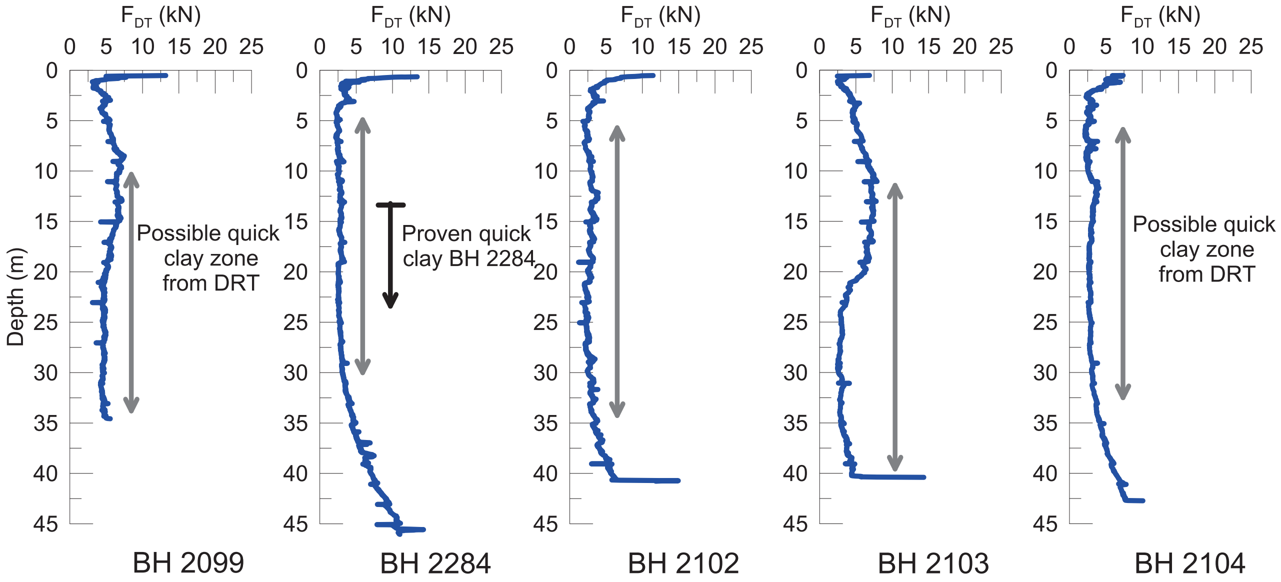
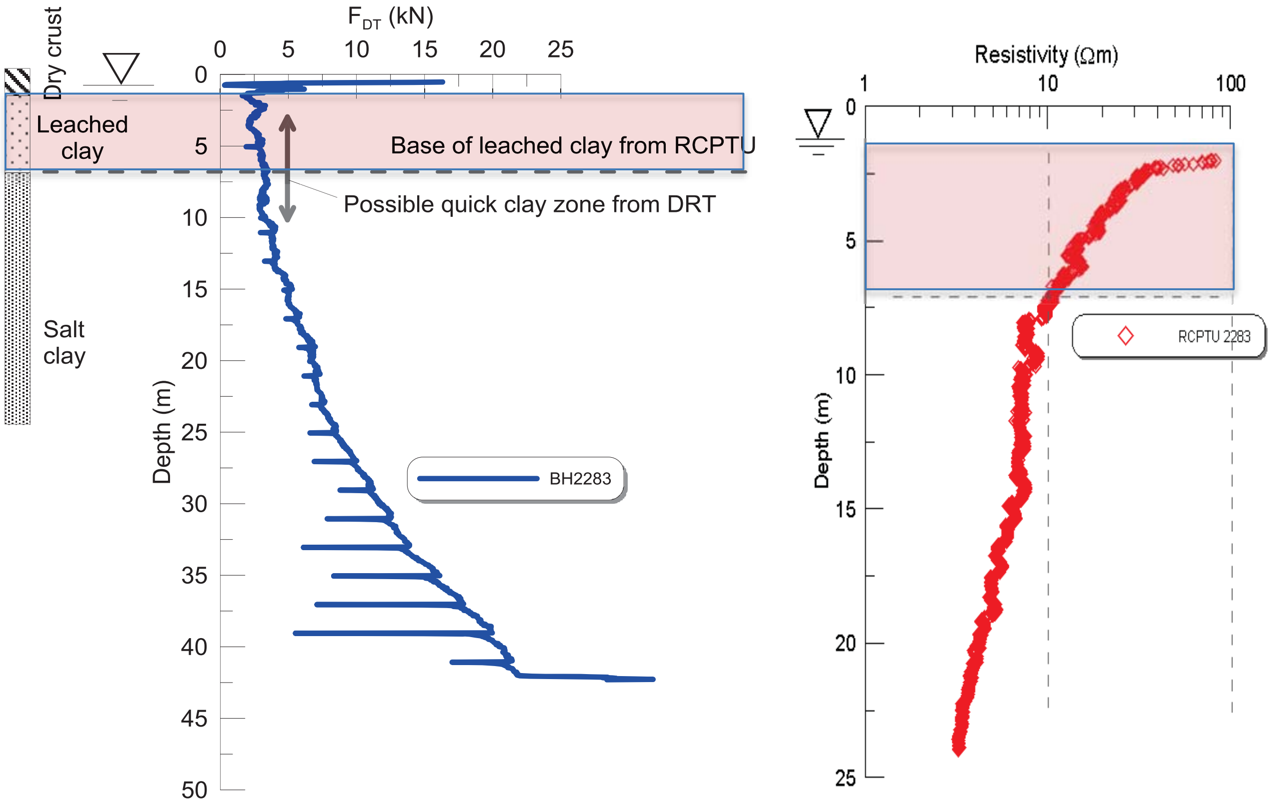


Figure C1.3 Rotary pressure soundings along ERT / AEM profile.



(a) Rotary pressure sounding (DRT)

Figure C1.4 Rotary pressure sounding and R-CPTU at borehole BH2283.

In areas where the thickness of soil layers was 10 m or more, the results indicate that AEM provides sufficient resolution to distinguish between salt and leached clay. This was investigated in further details by performing 2D ERT measurements that is known to provide sufficient resolution. Figure 3.16 in this report shows good agreement between AEM and ERT profiles near Vorma. In this area, thick deposits of sensitive, partly quick clay, were generally encountered. Rotary pressure soundings along the profile (se Figure C1.3) illustrates this well, with reduction or no increase in the penetration resistance with depth. Laboratory test results from sampling in borehole 2284 shows soft, but not sensitive clay from 0-13 m, then quick clay from 13-23 m where the deepest sample is collected. From the rotary pressure sounding, the transition to non-sensitive clay is indicated at 27 m. A borehole approximately 100 m from the profile shows the relation between resistivity values and the rotary pressure sounding. The rotary pressure sounding indicates presence of sensitive clays, but this was not confirmed by sampling and laboratory tests. The resistivity values obtained in R-CPTU are typical for quick clays in this area (see Figure C1.4), and the resistivity models from ERT and AEM show similar values.

The main conclusion is that AEM provides a quick overview of the ground conditions, and the results can be used for an adjusted and cost-effective boring plan. Modern AEM systems (SkyTEM) and precise processing and inversion of data provides resistivity models that almost resembles the accuracy and resolution obtained by surface measurements (ERT). This implies that AEM manages to capture the finer structures in the resistivity model for thick soil layers. Empirically, less than 10 m is a thin layer, but this limit may be stretched by numerical modelling. For depths to bedrock less than 10 m, the elevation for the bedrock contour may be determined, but the resistivity, and hence the basis for evaluation of leached clays, may be disturbed.

AEM is generally best suited for investigations over open areas, since the use is restricted near infrastructure and in urbanized areas.

Example C2: Site investigation for large areas

Project: Evaluation of the stability along Göta river. (GÄU sub-report 30, Løfroth et al, Linköping 2011).

To meet a changed climate and to better handle increased water volumes through Göta river, the Swedish government has consulted Statens geotekniska institutt (SGI) to carry out mapping and subsequent evaluation of the stability and slide risk along the whole Göta river valley. In the early stages of the project, data from previous investigations in the area were summarized and systematically organized, as a basis for new geotechnical and geophysical investigations.

One of the major scopes of the project was to investigate how use of 2D resistivity measurements on the surface (ERT), cone penetration tests with resistivity measurements (R-CPTU) and knowledge about the geochemistry of the soils could contribute to a more rational and complete ground investigations. In addition, recording of the total penetration force in a CPTU/R-CPTU was used for evaluation of the quick clay conditions. This was carried out in the same way as described in Chapter 3.2.2 in this report.

In the project area, 2D resistivity measurements (ERT) were carried out along profiles with directions normal to the riverbed. The locations of R-CPTU and locations for soil sampling were then chosen, based on information from the resistivity measurements and results from previous borings. In this way, an optimal and cost-efficient determination of the ground conditions could be obtained, since the additional borings were placed, based upon a suspicion of possible quick or sensitive clay layers.

The results from 2D resistivity measurements (ERT) show the distribution of resistivities in the soil volume along a profile on the surface. The presentation is a result of the inversion of a synthetic profile (pseudo-section), with stratification and resistivity values attached to nodes in the soil. The synthetic model is adapted to measured values of the potential through an iteration process, until agreement with the processed and measured data is obtained. The interpretation is inaccurate close to the ends of the resistivity profile. Every colour code in the profile represents an empirically based resistivity interval for a given type of soils. For example will resistivity values between 1 and 5-10 Ωm in this case correspond to salt, marine clay, whereas the interval 10 (5) - 30 Ωm usually corresponds to leached clay that possibly can be quick.

Figure C2.1 shows a typical resulting ERT-profile from this investigation, where the green / yellow-greenish areas represent leached clay, i.e. possibly quick or sensitive clay with resistivities in the order of 5 to 100 Ωm. The blue areas indicates intact, salt clay with resistivity values between 1 and 5 Ωm.

The lay-out of a 2D resistivity measurements is usually organized in longitudinal and cross-sectional profiles. By merging the processed profiles together in a so-called «fence»-diagram, one may be able to evaluate the interpretation of the profiles in the intersection between two profiles. Discrepancies in the interpretation along these axes will indicate larger than normal uncertainties in the interpretation. Figure C2.2 examplifies such interpretation, where the agreement between intersecting profiles is very good.

Use of resistivity data from R-CPTU measurements can principally be used to guide the interpretation of the ERT-profiles in single points, using constrained inversion techniques. This can be an advantage where the R-CPTU profiles have been performed to larger depths, since the resolution in the ERT-profiles normally becomes poorer at larger depths. However, the comparison is not without complicating factors, particularly for inhomogeneous conditions and irregular stratification in the ground. Here, 3D-effects will influence the interpretation of the ERT-profiles significantly, since the resistivity is influenced by the properties horizontally out from the profile line. Such effects are only marginally captured by the R-CPTU measurements, which are mainly influenced by the soil conditions in a zone corresponding to about 2,5 times the probe diameter.

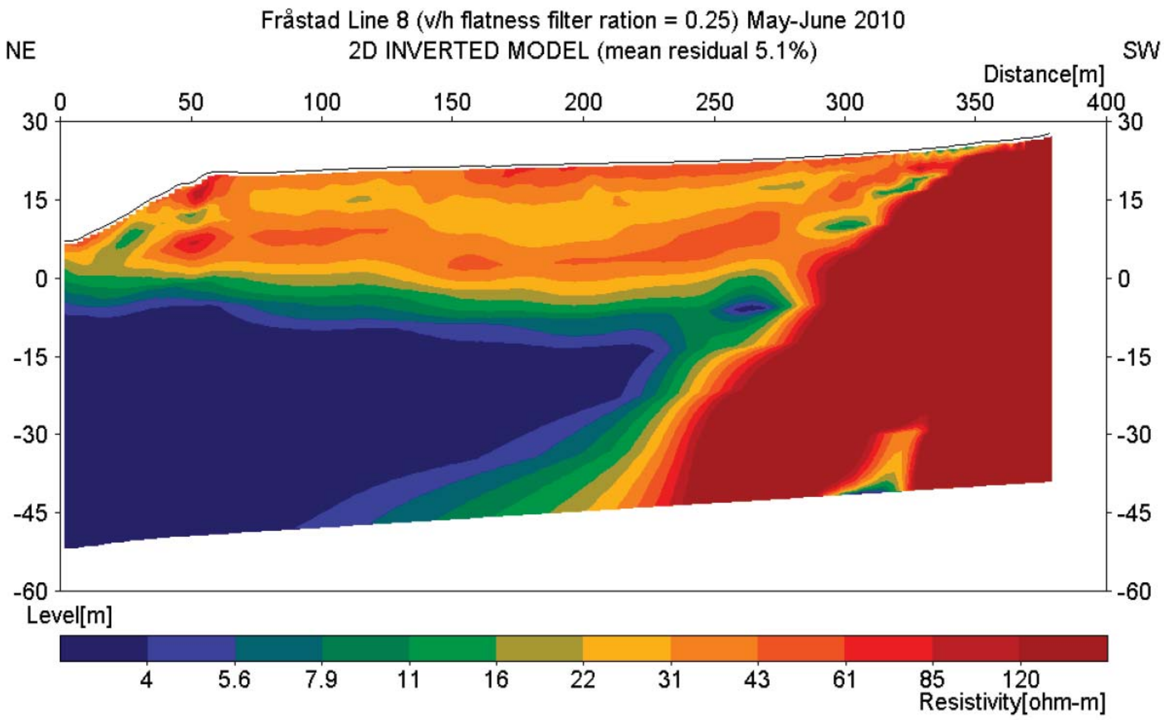


Figure C2.1 Typical result from a 2D ERT resistivity profile (Løfroth et al, 2011).

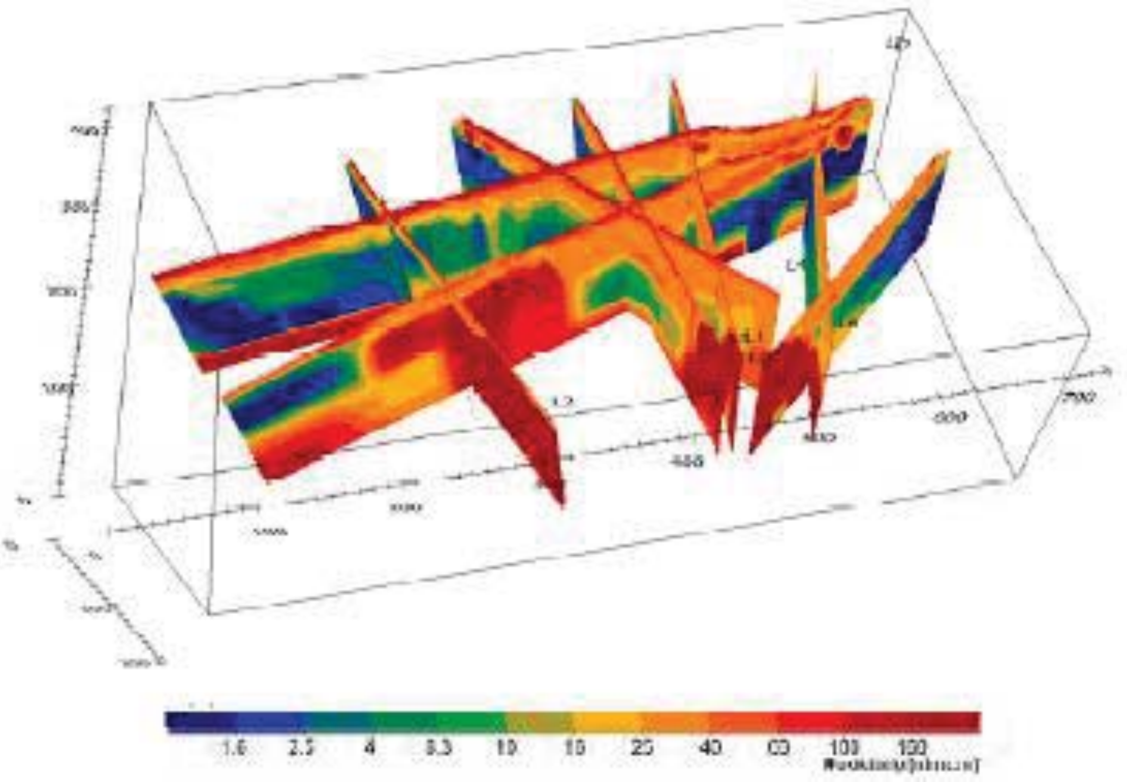


Figure C2.2 Summary of all ERT resistivity profiles within a project area. Quasi-3D presentation in a «fence»-diagram for control of the interpretation (Løfroth et al, 2011).

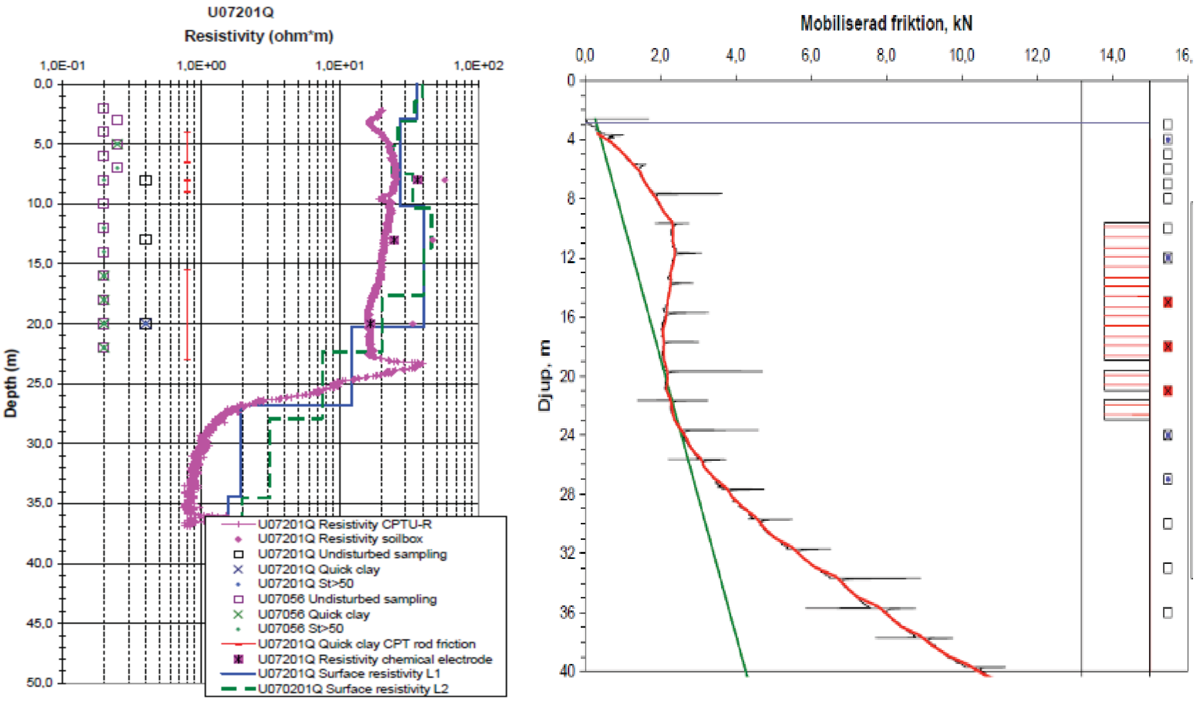


Figure C2.3 Summary of evaluated data in a selected part of the project area a) resistivity based b) rod friction based (Løfroth et al, 2011).

To control and compare results from all measurements with respect to identification of quick or sensitive clay, it may be convenient to gather information as shown on Figure C2.3a. Here, the results from ERT and R-CPTU are compared to other information, such as laboratory measured resistivity, remoulded shear strength and sensitivity from fall cone tests, as well as mobilized rod friction from CPTU.

Very good agreement was observed between interpretation of quick clay from mobilized rod friction and results from other methods and tests, see Figure C2.3b (right). However, this method tends to overestimate the amount of interpreted quick clay somewhat.

As a part of the project, extensive geochemical tests were carried out, both of the pore water and the mineral grains. It was particularly important to clarify the amount and type of dissolved salt ions. The results of the geochemical analyses showed that leached clays which were not sensitive/quick had a higher content of magnesium (Mg) and carbonate (CO_3) ions, which probably have been exchanged from the surface of the mineral grains through chemical weathering.

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