In situ detection of sensitive clays – Part II: Results

R. Sandven
Multiconsult, Norway, rolf.sandven@multiconsult.no

A. Gylland, A. Montafia
Multiconsult, Norway

K. Kåsin, A.A. Pfaffhuber
Norwegian Geotechnical Institute, Norway

M. Long
University College Dublin, Ireland

ABSTRACT

Sensitive and quick clays are typically found in Norway, Sweden and Canada, and are characterised by a remoulded undrained shear strength considerably lower than the undisturbed shear strength. In geotechnical engineering, the presence of sensitive clays poses a major challenge. The landslides at Rissa in 1978, and more recently at the Skjeggestad bridge in Norway, are devastating reminders of the potential threats related to such soils. In a construction project it is hence important to 1) determine if there is sensitive clay present and 2) clarify the extent of the quick clay deposit. This is currently done based on interpretation of soundings and to some extent geophysical methods such as electrical resistivity measurements. However, for verification of quick clay, sampling and laboratory testing must be performed.

Here, a set of updated and new guidelines for classification of sensitive clays from in-situ measurements are presented. The aim is to provide the geotechnical engineer with a practical classification tools where all available information is utilized and combined efficiently. The classification tools are based on results from methods such as conventional soundings, CPTU with measurement of total force, electrical field vane testing in combination with geophysical methods such as R-CPTU, 2D resistivity profiles (ERT) and airborne electromagnetic measurements (AEM). The methods, and how they are utilized in investigation strategies for detection of quick and sensitive clays, have been described in another paper to this conference. An extensive database of Norwegian test sites forms the basis for the work. The results from this study show that the above mentioned site investigation methods holds information that complements each other, to form a solid basis for detection of sensitive clays. In turn, this opens for more efficient site *investigations where all available data are interpreted in a systematic manner to produce a reliable map of sensitive clay deposits.*

Keywords: Quick clay, geotechnical investigations, resistivity measurements, interpretation.

1 INTRODUCTION

1.1 The NIFS project

The NIFS project is a joint venture between the Norwegian Water Resources and Energy Directorate (NVE), The Norwegian Railroad Administration (NNRA) and the Norwegian Public Roads Administration (NPRA). One of the goals of the project is to coordinate guidelines and develop better tools for geotechnical design in quick clay areas.

Work task 6 in this project focus on Quick clay, where a study on *"Detection of brittle materials"* has been carried out. The results reported herein are based on results from this study, where various new and existing criteria for detection of quick and sensitive clays have been evaluated. Reference is made to the reports NIFS report no. 2015-126 and 2015-101 for detailed results and soil data (www.naturfare.no).

1.2 Scope of work

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

- Evaluation of conventional sounding methods and their ability to detect brittle materials (rotational weight sounding DT, rotational pressure sounding DRT and total sounding TOT)
- Suggest improved CPTU-based identification charts for classification of brittle materials
- Evaluation of resistivity measurements for mapping of quick clay deposits (downhole mode (R-CPTU), surface mode (ERT) and airborne mode (AEM))
- Evaluate and compare results from electrical field vane tests (EFVT)
- Evaluate correlations between resistivity values from R-CPTU and ERT with results from index tests and salinity measurements
- Recommended site investigation strategy based on integrated geotechnical and geophysical methods for detection of quick and sensitive clays

The following methods have been included in the study:

- Rotary weight sounding (DT)
- Rotary pressure sounding (DRT)
- Total sounding (TOT)
- Cone penetration tests (CPTU)
- Piston sampling (ϕ54 mm, ϕ76 mm) (PS)
- Block sampling (ϕ250 mm Sherbrooke, ϕ160 mm NTNU) (BS)
- Electric field vane test (EFVT)
- Cone penetration tests with resistivity measurement (R-CPTU)
- Surface resistivity measurements (ERT)
- Airborne Electromagnetic Measurements (AEM)

Table 1 provides a detailed overview of the investigations carried out at the most important test sites.

Table 1 Test program on important selected test sites.

Test site	Methods
Smørgrav	DT, CPTU, R-CPTU, ERT, PS
Kløfta	TOT, CPTU, R-CPTU, ERT, AEM, PS, BS
Klett	DT, TOT, CPTU, R-CPTU, ERT, EFVT, PS, BS
Fallan	TOT, CPTU, R-CPTU, ERT, EFVT, PS
Tiller	TOT, CPTU, R-CPTU, ERT, EFVT, PS, BS
Esp, Byneset	TOT, CPTU, R-CPTU, ERT, EFVT, PS, BS
Dragvoll	CPTU, R-CPTU, ERT, BS
Tiller	CPTU, R-CPTU, ERT, PS, BS, EFVT
Rissa	TOT, DRT, CPTU, R-CPTU, PS, BS

2 SELECTED RESULTS FROM THE STUDY

2.1 Conventional sounding tests

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 force and the remoulded shear strength for the clay. This correlation is however influenced by the diameter of the drillrods, the tip design, the ratio between tip and rod diameter, the penetration principle (rotation, pressure, dynamic) and finally the penetration rate.

The detection of brittle materials by conventional sounding methods may however be influenced by features in soil composition and layering, such as:

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

In most soils, the increasing friction along the drillrods will result in an increasing penetration force with depth. In a sensitive or quick clay, an increase in the friction component is close to zero. Hence, no increase in penetration force will be noticed, resulting in the characteristic vertical curve in sensitive clays. In addition, the collapse behaviour of quick clays may in some cases result in a negative slope of the curve.

When drilling through a dense, thick top layer, the friction in this layer may influence the sounding profile considerably. Figure 1 shows examples of sounding profiles with and without predrilling through a 10 m thick dense top layer. The results show that the quick clay layer is identified reasonably well after predrilling through the top layer (Figure 1 right), whereas it is not revealed when the sounding is commenced at the surface (Figure 1 left). If deposits of brittle materials are expected at a site, one should hence predrill through present top layers, to better reveal possible underlying sensitive strata.

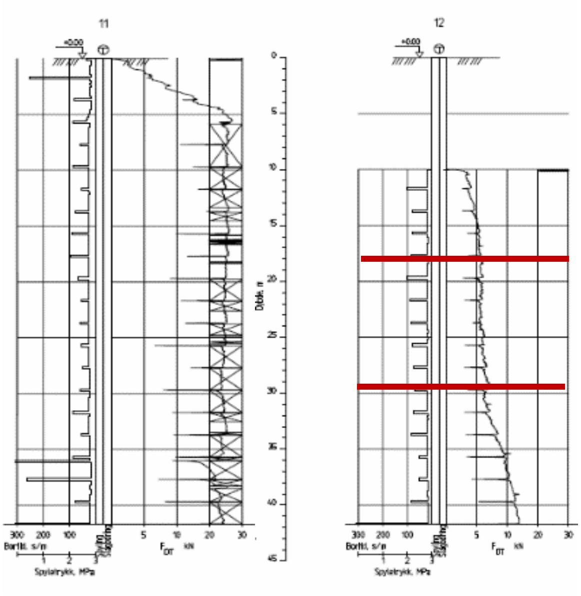

Figure 1 Total sounding profile in quick clay deposit with and without predrilling (NIFS-report 2015-126).

2.2 Cone penetration tests (CPTU)

CPTU has a great potential for detection of quick and sensitive layers through measurements of cone resistance, sleeve friction and pore pressure. Despite the obvious potential in these measurements, mixed experiences exist with CPTU for detection of brittle materials. The reason may be that the results obtained are influenced by other factors, not related to the clay being sensitive or not. As a result of the NIFS study, new and alternative interpretation CPTU data have been introduced, and some of them are elaborated in the following.

2.2.1 New identification charts

A series of soil identification charts have previously been developed, but they appear in many cases to be misleading for indication of sensitive Norwegian clays. One aim of this study has hence been to develop new classification charts for classification of sensitive clays, based on the following approaches:

- Use of revised cone resistance number N_{mc} (based on the preconsolidation stress)
- Use of revised pore pressure ratio B_{q1} (based on the estimated pore pressure at the cone face)

The cone resistance number is defined as:

$$N_m = q_n/(\sigma_{vo}' + a) \qquad (1)$$

where:

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

a= attraction (kPa)

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:

$$N_{mc} = q_n/(\sigma_A' + a) \qquad (2)$$

where:

σ_A'= reference stress (see Eq.(3)) (kPa)

To introduce the preconsolidation stress and also to account for swelling effects, the expression shown in Eq.3 is used as reference stress σ'_A, similar to the approach used by Ladd & Foott (1974) in the SHANSEP-adaption. The stress exponent m account for the effect of unloading and swelling of the sediment.

$$\sigma'_A = \sigma'_c{}^m \cdot \sigma'_{vo}{}^{(1-m)} \qquad (3)$$

where:

σ_c'= preconsolidation stress (kPa)

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

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

The stress exponent m is derived from experience of the active undrained shear strength in Norwegian clays, with m in the order of 0,7 - 0,8. This expression requires reliable values of the preconsolidation stress σ_c' so that a $\sigma_c' - z$ profile can be established. The preconsolidation stress should primarily be determined from oedometer test data, from known topographical information and previous terrain level, secondarily from independent interpretation of CPTU data. Empirical relations between over-consolidation ratio OCR and pore pressure distribution around the probe can also be used (see e.g. Sully et al, 1988), see Eq.4:

$$u_1 = u_2 + u_o * (OCR-0,66)/1,43 \qquad (4)$$

where:

u_1= pore pressure at the conical tip (u_1 usually > u_2) (kPa)

u_2= pore pressure at reference level behind conical tip (kPa)

u_o= in situ pore pressure before penetration (kPa)

OCR= overconsolidation ratio ($=\sigma_c'/\sigma_{vo}'$) (-)

The revised expression for the pore pressure ratio B_{q1} hence becomes:

$$B_{q1} = (u_1-u_o)/(q_n) = (k*(u_2-u_o))/q_n \qquad (5)$$

where:

k= experience based correction factor expressing the ratio between the pore pressure at various locations on the probe (-)

Tentative values of k in various clays are given below:

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

The combination of N_{mc} and B_{q1} is used in a simple identification chart for sensitive clays, see Figure 2. The figure includes datapoints from all sites included in the study.

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

This approach represents some uncertainty due to the utilized empirical relationships between u_1 and u_2, and it may hence be relevant to use B_{q2} since this pore pressure ratio is based on the measured pore pressures.

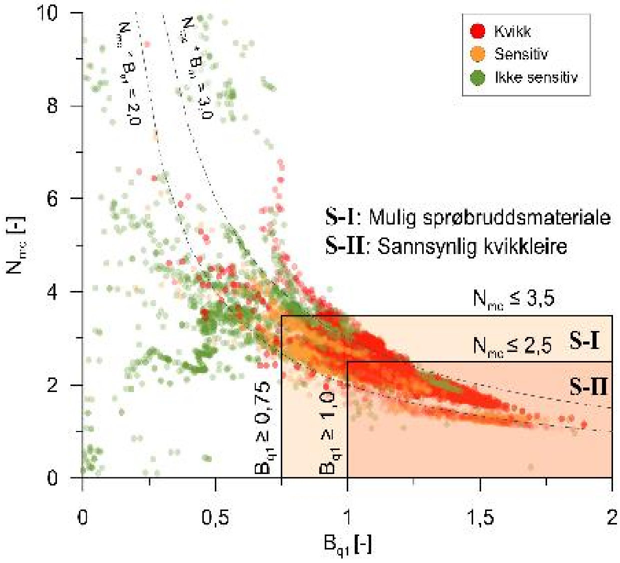

Figure 2 New identification chart for brittle materials based on N_{mc} and B_{q1} (NIFS-report 2015-126).

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. In the data sets, there are certainly some discrepancies, but for most test sites very good agreement is obtained.

2.2.2 *Interpretation of sleeve friction*

In 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, see Eq.6.

$$R_{fu} = f_s * 100\,\% / \Delta u_1 \qquad (6)$$

where:

f_s= measured sleeve friction (kPa)
Δu_1= u_1-u_o, corrected excess pore pressure at the conical tip (kPa)
u_o= in situ pore pressure (kPa)

This formulation has the added effect that materials with distinct differences in pore pressure response becomes easier to classify and with less scatter.

This principle is used in Figure 3, 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. Based on this, the following classification is suggested:

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

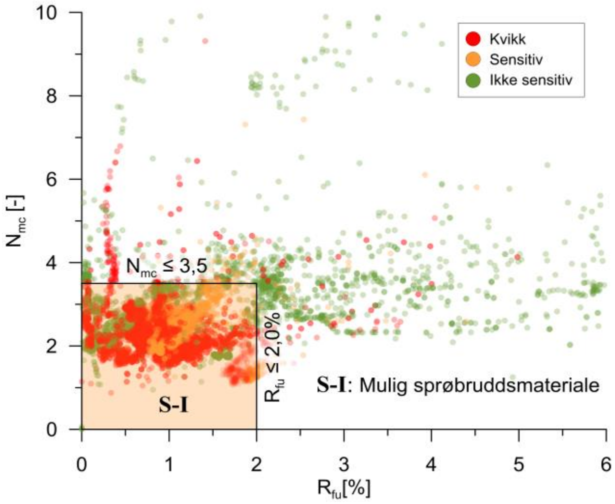

Figure 3 New identification chart based on N_{mc} and R_{fu} (NIFS-report 2015-126).

The sleeve friction is however an uncertain parameter to use for detection of quick clays due to reasons discussed earlier.

2.2.3 *Interpretation of rod friction*

After penetration of the CPTU-probe, the sleeve friction may not represent a fully remoulded condition. This means that the evaluation of quick clay from the sleeve friction (f_s) may be misleading. The rod friction will however represent remoulded conditions according to the continued penetration of the rods into the ground. After continuous penetration of the rods, the remoulding of the materials will gradually become more complete along the drillrods. The friction may hence be determined as the average friction along the drillrods.

In the interpretation of the rod friction, the weight of the drillrods and the tip force is subtracted from the total thrust, see Eq.7. The total rod friction Q_s can then be determined as a function of penetration depth:

$$Q_s = F + G - q_t * A_c \qquad (7)$$

where:

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

The curve for the calculated friction along the rods can be determined by a theoretical line, corresponding to an evenly distributed friction of 0,5 kPa (quick clay definition) or 2,0 kPa (brittle material definition). For quick clays, the slope of the friction force Q_s should be less than the slope for the theoretical line corresponding to 0,5 kPa sleeve friction.

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 made in the Swedish Göta älv project (Löfroth et al (2011)). It is recommended to record the total penetration force routinely in a CPTU.

2.3 Vane testing

In the interpretation of shear strength from a vane test, it is assumed that the mobilization of shear stresses is evenly distributed at the cylindrical failure surface. The shear strength can hence be determined from the following expression:

$$c_{u,rv} = 6T/7\pi D^3 \tag{8}$$

where:

T= measured torque (Nmm)
D= vane diameter (mm)

To determine the undisturbed undrained shear strength (c_{uv}), the maximum torque T_{max} is used.

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. To utilize this curve, the test must be run to minimum 90° rotation of the vane, so that a full failure circle is defined. A method for utilization of the remoulding energy of clays for landslide runout evaulations is currently developed developed, based on vane test results (Thakur et al. 2015).

For determination of the remoulded shear strength (c_{rv}), the measured residual torque after remoulding of the clay is utilized. A quick clay has by definition a remoulded shear strength of $c_{rv} < 0{,}5$ kPa.

The complete remoulding of the clay is obtained by applying 25 full rotations of the vane. When the clay in the zone around the vane 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 remoulding, to avoid excessive pore water 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. A corresponding rotation of ca. 5^o is recommended for reading of the torque in the remoulded state.

Conventionally, the torque is applied and measured at the top of the drillrods. The transfer of the applied torque down to the vane will however be influenced by friction and deformations in the rod system, and some of the torque will be lost before it reaches the vane. This friction will typically be around 1-3 Nm, and will increase somewhat with depth. It may be reduced by proper maintenance, lubrication and sufficient cleaning of the vane equipment.

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 hence challenges the resolution of the equipment. For determination of the undisturbed undrained shear strength, the necessary resolution is expected 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, even with modern equipment, but electric vanes are at least better than the manual. 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.

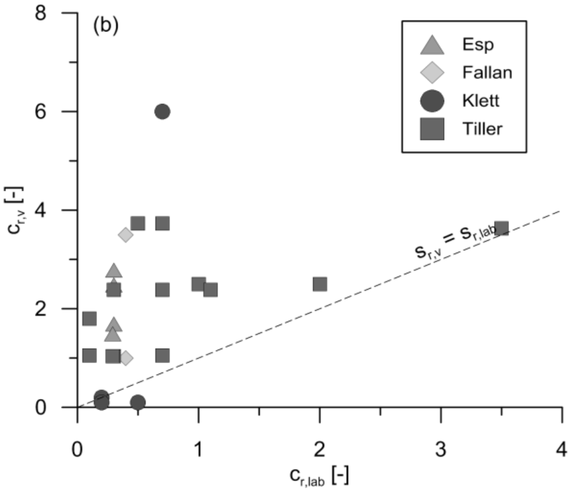

Figure 4 Comparison between remoulded shear strength obtained in field vane and fall cone tests (units in kPa) (NIFS report 2015-126).

Figure 4 shows a summary of the remoulded shear strength measured by vane tests and fall cone tests in the laboratory. The results clearly show that vane tests with measurement of the torque on top of the drillrods overestimate the remoulded shear strength in brittle materials for depths below > 10-15 m.

Measurement of the remoulded shear strength is one of the attractive features with vane testing when it comes to detection of brittle materials. At the same time, it is evident that the method has obvious limitations when it comes to measurements of this parameter, particularly if 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 measure the torque down at the vane.

2.4 Resistivity measurements

The electric resistivity of soils is generally a function of porosity, the ion content of the pore water, salinity, clay content and content of charged minerals such as graphite and some sulfides.

For clays, it is mainly the salt content that influences the resistivity, at least for salinities higher than about 1 g/l (Montafia, 2013). The resistivity will hence be higher in brittle materials than for intact marine clays. Table 2 summarizes the resistivity in various geological materials based on Norwegian experiences. By measuring the resistivity of the soils, one may hence be able to detect potentially leached zones according to the classification values in Table 2. It is emphasized that local site specific variations from the tabulated values may occur.

Table 2 Resistivity in geological materials (after Solberg et al (2008)).

Soil type	**Resistivity** (Ωm)
Salt, marine clay	1 – 20
Leached clay	20 – 90
Dry crust, coarse materials, sand and gravel	70 – 300
Silt, saturated	50- 200
Sand, saturated	200 - 1000
Rock	Several 1000

2.4.1 Identification of leached zones

Resistivity measurements on the 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 can be used to get an overview of the homogeneity of the sediments. Since the resistivity of the clay primarily is determined by the salt content, a resistivity model can be established and indicate the extension of layers of leached and possibly quick clay. If the results from ERT-measurements are available before the geotechnical borings are carried out, the boring plan can be developed based on the interpreted resistivity model.

ERT can also be used in steep areas where drillrigs cannot access, for example in 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 borings alone.

The resistivity is however not a unique measure of a leached clay. High resistivity can be caused by a lower salt content, but may also by due to high silt content. It is hence recommended to always calibrate the resistivity model by geotechnical borings.

Using constrained inversion, one include other available information in the processing of the resistivity profile, for example location of the rock surface from total sounding or measured resistivity from R-CPTU. This will generally improve the interpretation of the resistivity models.

Resistivity measurements from airplanes or helicopters (Airborne Electromagnetic Measurements AEM) may be used for detection of brittle materials in more or less the same way as for ERT. AEM produces models for the electric resistivity in a regional scale, along profiles of almost unlimited length and several hundred meters penetration depth. Use of AEM is favourable in regional mapping at an early investigation stage, in large projects or in large-scale mapping of clay deposits.

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 a limited project area. AEM has somewhat poorer resolution than ERT, and the method cannot be used over urban areas or roads with dense traffic.

Modern 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 (some tens of meters), the AEM resolution may hence be sufficient to detect differences in the resistivities between salt and leached clays.

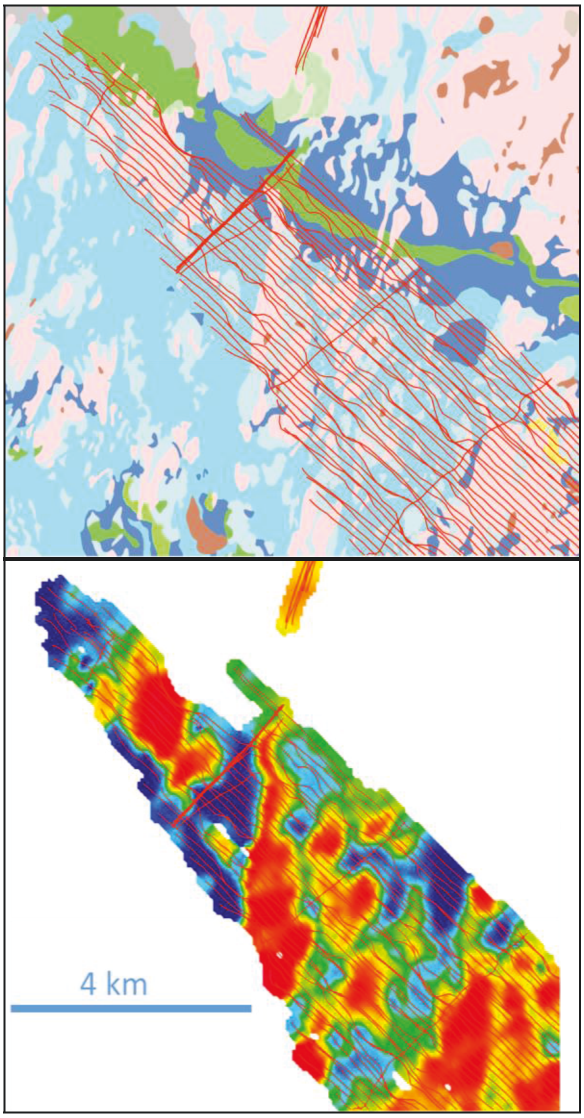

Figure 5 Example of results from AEM in a quick clay area. Upper: Quaternary soil map (NGU) and AEM flylines. Lower: AEM resistivity section from 0-15 m depth.(NIFS rep. 2015-126). Legend geology: Blue: marine deposits, Green: moraine, Pink: rock exposures, Brown: bog. Legend resistivity: Blue 1 Ωm to Red 1.000 Ωm.

2.4.2 Comparison of R-CPTU, ERT and AEM results

The difference in resolution between the three methods for resistivity measurements is important to be aware of when comparing results obtained with these methods. The measurements are representative for a soil volume ranging from some centimeters to some tens of centimeters for R-CPTU, some meters or 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 by R-CPTU, but will show a gradual transition in presentation of ERT- and AEM-data. Except from these conceptual limitations, experience show that the measurements agree well where the soil conditions are favourable.

3 CONCLUSIONS AND FINAL REMARKS

A combination of geophysical and geotechnical methods have become more usual in modern ground investigations, particularly in larger projects. In such integrated measurements, geotechnical engineers and geophysicists cooperate closely, and by joint knowledge decide where geotechnical soundings, in situ tests and sampling should be located for optimal cost-efficiency.

The penetration force for different sounding methods are influenced by several features such as effect of top layers, increasing rod friction by depth and previous consolidation. 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 at larger depths. Predrilling through such layers is generally recommended. Moreover, it is a general impression that conventional soundings tend to overestimate the thickness of the quick clay layers.

Existing soil identification charts for CPTU often give misleading classification of brittle materials for various reasons. It is recommended to use new identification charts for quick and sensitive clays presented herein. These charts consider the stress history of the materials, together with the estimated pore pressures in the failure zone beneath the probe (u_1).

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 sleeve friction/rod friction. In this way, a wider basis for classification and interpretation of the results is obtained. The experiences from this study shows that the quick clay layer for all sites plots within the expected variation range of 10 - 100 Ωm. Measured resistivity values outside the reported range may hence with large reliability be classified as non-leached clays, even if some non-sensitive clays also show resistivities in this range.

It is recommended to measure the resistivity in a CPTU if a resistivity module is available, since this procedure only requires a marginal increase in test duration. Furthermore, local correlations between resistivity values and other soil properties may be established by relating R-CPTU results with other field or laboratory data. Such site specific relationships may be more precise than general expressions.

Use of ERT- and AEM-methods gives approximately the same resistivity values as R-CPTU, and there is generally good agreement between the three methods, particularly in homogenous soils. One major advantage obtained with these methods is the continuous information of soil layers in the ground, something that is very important in evaluation of slope stability, possible slide extension and run-out distance for the remoulded and liquefied slide debris.

A field vane test traditionally gives information about the in situ undrained shear strength (undisturbed and remoulded), and hence the sensitivity. Modern electrical systems give possibilities for measurement of the friction using an electro-mechanical unit applying the torque. For these systems it is required that the torque is measured at the vane, to avoid important sources of errors in the measurements. Such equipment is now commercially available. If the torque is measured at the top of the drillrods it is shown that the measured torque is heavily influenced, particularly for remoulded conditions. Consequently, it is not recommended to use the method for determination of the remoulded shear strength of quick clay for depths exceeding 10 m.

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.

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 to the large scatter in measured resistivity in leached clays.

None of the methods reported herein are without the possibility of misleading interpretation, and the evaluation of results requires critical judgement and caution. The integrated use of geophysical and geotechnical measuring methods makes each of the approaches stronger and will be the recommended strategy in larger projects,

4 ACKNOWLEDGEMENTS

The partners in the NIFS project are greatly acknowledged for the financial support and good discussions throughout the study. The board of the Norwegian Geotechnical Society (NGF) are acknowledged for financial support for development of the summary report. The authors want to extend thanks to Rambøll, Multiconsult, NGI, Statens vegvesen (NPRA) and NGU for allowing the use of data in the study.

5 REFERENCES

Anschütz, H., Bazin, S. and Pfaffhuber, A. (2015). Towards using AEM for sensitive clay mapping – A case study from Norway. 1st European Airborne EM conference. Torino, Italia, Mo AEM 04.

Ladd, C.C. and Foott, R. 1974. New design procedure for stability of soft clays. Journal of the Geotechnical Engineering Division, ASCE, 100(7), pp.763–786.

Löfroth, H., Suer, P., Dahlin, T., Leroux, V. and Schälin, D. (2011). Quick clay mapping by resistivity - Surface resistivity, CPTU-R and chemistry to complement other geotechnical sounding and sampling. Statens Geotekniska Institut, SGI. Göta älv utredningen. GÄU. Report 30. Statens Geotekniska Institut, Linköping, Sverige.

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.

NIFS (2015). Detection of brittle materials. Summary report with recommendations. Final report. NIFS Report no. 126/2015 (www.naturfare.no)

NIFS (2015). Detection of quick clay by R-CPTU and electrical field vane tests. Results from field study (in Norwegian). NIFS Report no.101/2015 (www.naturfare.no)

Solberg, I. L., Rønning, J. S., Dalsegg, E., Hansen, L., Rokoengen, K. and Sandven, R. (2008). Resistivity measurements as a tool for outlining quick-clay extent and valley-fill stratigraphy: A feasibility study from Buvika, central Norway. Canadian Geotechnical Journal, 45(2), pp.210-225.

Sully, J.P., Campanella, R.G. and Robertson, P.K. (1988). Overconsolidation ratio of clays from penetration pore water pressures. ASCE Journal of Geotechnical Engineering, ASCE, 114 (2), pp.209-15.

Thakur, V., Degago, S., Gylland, A.S. and Sandven, R. (2015). In-situ measurement of remolding energy of sensitive clay. GEOQuebec 2015 – Challenges from north to south, Quebec, Canada, september 2015.