In situ detection of sensitive clays – Part I: Selected test methods

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ABSTRACT
Sensitive and quick clays are typically found in Norway, Sweden and Canada, and are characterized by a remoulded undrained shear strength that is considerably lower than the undisturbed shear strength. In geotechnical engineering, the presence of sensitive clays pose 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. For a geotechnical engineering 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 by geophysical methods such as electrical resistivity measurements. However, for verification of quick clay, sampling and laboratory testing must be performed. Here, a set of methods for classification of sensitive clays from in situ measurements are presented. The aim is to provide the geotechnical engineer with practical and rational methods, from which all available information is utilized and combined efficiently. The methods presented herein include conventional soundings, CPTU with measurement of total force, vane shear testing in combination with geophysical methods such as R-CPTU, 2D resistivity profiles (ERT) and airborne electromagnetic measurements (AEM). An extensive database of Norwegian test sites forms the basis for the work. This paper describes the methods utilized in this study and how they may be combined in a strategy for detecting deposits of quick and sensitive clays. The major results from the study are presented in another paper presented to this conference.

Keywords: Quick clay, geotechnical investigations, resistivity measurements.

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 main 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 the detection and behavior of quick clays, where a study on *"Detection of brittle materials"* has been carried out in the period 2012-2015. This report concludes this study, giving recommendations of methods and procedures for detection of brittle materials from various field and laboratory tests. Various new and existing criteria have been tested and evaluated on test results from a number of test sites. 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 Background

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 give sufficient indications of brittle materials in many cases. However, sounding profiles obtained by conventional methods may give misleading indications in some situations. This may either be on the conservative side, where results indicate quick clay in the field, but where the laboratory testing show non-sensitive behaviour. More difficult is the opposite, where the sounding profiles show no signs of quick clay, but where such materials are discovered later in the project.

The great efforts undertaken for mapping of quick clay zones have led to an increasing need of quicker and more reliable identification of such materials. Today, there is an increasing tendency of using a combination of geophysical and geotechnical methods in mapping of quick and sensitive clays. In general, one may say that geophysical methods cover large areas in relatively short time, but possibly with poorer resolution and less refinement than most geotechnical tests. By combining geophysical and geotechnical methods, the outcome may hence be a more rational and cost-effective ground investigation, see e.g. Löfroth et al (2011).

1.3 Scope of work

The methods applied in mapping of brittle materials must be chosen based on a cost-benefit perspective, the applicability of the methods for the actual ground conditions and the general use of soil data in the project. In this work, it has been important to present recommendations based on the experiences and observations made with various detection methods. In particular, this is valid for the resistivity methods R-CPTU, ERT and AEM, where limited experiences exist from practical use.

The work carried out in the study 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

1.4 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 Guideline 7/2014 for planning and development of quick clay areas.

Quick clay: Clay that in its remoulded state has a measured shear strength c_r less than 0,5 kPa.

Sensitive clay: Clay showing a certain level of strength loss in the remoulded state. 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 = sensitivity = ratio between intact, undisturbed undrained and remoulded undrained shear strength).

Brittle behaviour: Brittle materials are clays and silts that exhibits strain softening for strain levels beyond the failure strain. The NVE guideline classifies all materials with a remoulded shear strength c_r < 2,0 kPa and sensitivity S_t > 15 as brittle materials. Both criteria have to be satisfied.

2 SELECTED TEST SITES

In the NIFS-project, two new test sites were established (Klett and Fallan), which are documented in NIFS report R101-2015 (www.naturfare.no). In addition, several other well-established test sites have been included, either by research studies or in commercial projects. The following investigation 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 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

3 DETECTION METHODS

3.1 Conventional soundings

Conventional sounding methods such as rotary pressure and total sounding use, directly or indirectly, the measured total penetration force for indication of brittle materials.

3.1.1 Rotary pressure sounding (DRT)

Rotary pressure sounding is a method where the drillstring is pushed and rotated into the ground. by a drillrig. During penetration, the procedure shall satisfy the following conditions:

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

The sounding resistance corresponds to the penetration force required to obtain these normative conditions.

Rotary pressure sounding can be used in most types of soils, from clay to gravel. The results are used for interpretation of soil stratification and the depth to firm layers or bedrock. The sounding profile may also be used for an experience-based interpretation of soil type.

3.1.2 Total sounding (TOT)

Total sounding is used to determine soil stratification and depth to dense strata. The method also enables drilling through larger stones and penetration of the bedrock surface. Total sounding requires a hydraulic drillrig with a percussion hammer and flushing possibilities.

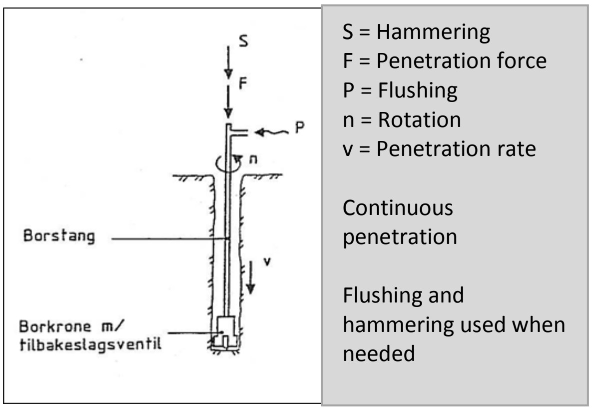

Figure 1 Test principles for total sounding.

Total sounding combines the sounding principles from rotary pressure sounding and rock control drilling, see Figure 1. In rotary pressure mode, the drill rods are penetrated into the ground with constant penetration and rotation rate. If these methods are not sufficient to advance the drillrods, it is possible to switch to rock control mode with increased rotation, then flushing and hammering.

Detection of brittle materials from rotary pressure and total soundings is mainly based on the shape of the sounding curve, to a lesser degree the magnitude of the recorded penetration force.

3.2 Cone penetration tests (CPTU)

In Norway, the Cone Penetration Test with pore pressure measurement (CPTU) is one of the most used methods nowadays. The test is performed with an instrumented cylindrical probe with conical tip that is penetrated into the ground at a constant rate of 20 mm/sec. The probe contains electronic transducers for recording of the load against the cone, the force against the friction sleeve and the pore pressure at the location of the porous filter. A location immediately above the cone tip is selected as reference level for the pore pressure measurement (u_2). In addition, the recording of the total penetration force may be used to deduct the mobilized friction along the drillrods. This information can be used to detect layers of quick and sensitive clays.

The accuracy of CPTU measurements is organized in four Application classes (1-4). Application class 1 (best class) is used for soft to very soft, homogenous soil conditions and is always required for design evaluations in quick clay areas (NVE, 7/2014).

The presence of quick or sensitive clays from CPTU may be evaluated from the following results:

- Net cone resistance (q_n) – sounding depth (z) (or effective overburden stress (σ_{vo}')).
- Sleeve friction (f_s) or friction ratio ($R_f = f_s$*100 % /q_n) – sounding depth (z).
- Pore pressure ratio ($B_q = \Delta u/q_n$) – sounding depth (z).
- Use of available soil identification charts

Despite the obvious potential in these approaches, mixed experiences exist with CPTU in 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. This is further elaborated in the following.

Sleeve friction f_s

A completely remoulded quick clay has a shear strength c_{ur} < 0,5 kPa. Hence, the material is close to being a liquid after full degradation of the soil structure. In CPTU, this should result in a very small mobilized sleeve friction along the 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, even in quick or sensitive clays. This is often the case in silty, lean clays, where the material requires several repeated penetration cycles of the probe before full remoulding is obtained.

Pore pressure ratio B_q

The pore pressure ratio $B_{q2} = \Delta u_2/q_n$ may be an efficient indicator of quick or sensitive NC clays. In these clays, $B_q \geq 1,0$ is common due to the collapsible behaviour at failure, associated with large excess pore pressures.

In stiffer, overconsolidated clays, the B_{q2} – values in quick clays are usually significantly lower, often between 0,6 and 0,9 depending on the overconsolidation ratio. Due to dilatancy effects, the measured pore pressures behind the cone are smaller than the pore pressure in the compression zone beneath the tip (u_1). Due to this influence, the pore pressure ratio B_q is not a unique identification parameter in brittle materials, and a pore pressure ratio based on u_1 (B_{q1}) might be better suited.

3.3 Vane testing

Vane testing can be used to determine the undrained shear strength in clays. Both intact (c_{uv}) and remoulded shear strength (c_{rv}) can be found. The vane test is the only in situ test method which can be used to determine the remoulded shear strength and the sensitivity ($S_t = c_{uv}/c_{rv}$) directly.

A complete set of field vane equipment consists of a lower part with the vane protection shoe, a set of inner rods with the vane mounted on the tip, outer rods and a recording instrument. The vane consists of four rectangular plates in cruciform shape.

The 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, an increasing torque is applied on the inserted vane, until the material adjacent to the vane reaches failure. The corresponding maximum torque is recorded, and enables determination of the undrained vane strength c_{uv}. The test should reach failure in 1-3 minutes with a rotation rate of about 0.2°/sec. The remoulded shear strength (c_{rv}) is determined after at least 25 full, rapid rotations of the vane.

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 small stones interfere with the vane, this may influence the measured values significantly. Moreover, it is important that the vane position is fixed during the measurements. If the vane is sinking or lifted during the measurements, it may result in a higher torque since parts of the vane then will rotate in an undisturbed or partially disturbed material.

3.4 Resistivity measurements

The resistivity is a measure of the ability of soils to conduct electric 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 resistivity gives information about the soil layers, and may in this context indicate the salt content in the ground water.

The computed resistivity from the measurements is an apparent resistivity. This will be identical to the real resistivity in the ground if the material is homogeneous. If the ground is non-homogeneous, the apparent resistivity from a weighted average of the resistivity in individual layers can be used.

Resistivity measurements seem to have a great potential for detection of brittle materials and the extent of the deposit. Resistivity profiles give a continuous image of the ground layering, where local information from geotechnical borings may be used to support the geophysical interpretation.

So far, the most popular geophysical 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 R-CPTU. Recently, airborne electromagnetic measurements (AEM) have been introduced for mapping of leached clays. This method is now regarded as a very efficient method for mapping of large areas and investigations for road or railway projects.

3.4.1 Downhole measurements (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. 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.

Figure 2 Example of R-CPTU probe (NIFS-report 2015-126).

Scandinavian manufacturers of R-CPTU equipment have chosen to manufacture their 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.

Application of current in the soil is not similar for all probe types. Some probes send short impulses of DC current into the soil, whereas others use AC current, where the intensity can be adjusted. The resistivity module is usually calibrated by 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 for the measurements.

The additional time for R-CPTU compared to a conventional CPTU is only a few minutes. This is the time needed to mount the resistivity module on the battery package. Apart from that, the sounding procedure is similar.

3.4.2 Surface measurements (ERT)

Electrical resistivity tomography (ERT) is a geophysical method that uses DC current for measurement of the resistivity distribution in the ground, see test principle in Figure 3. The current is applied to the soil volume by using short steel electrodes. These are installed from the surface, penetrating 10-20 cm into the ground. By evaluating the differences in electric potential, a measurement of the soil resistance is obtained for all electrode locations. With the aid of an inversion algorithm, a 2D or 3D resistivity model of the ground is processed from the results, see Figure 4. By comparing the resistivity model with data from geotechnical borings, supported by 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 soil resistivity is determined by sediment or rock type.

The measurement profiles are organized in one or more straight lines in the terrain. Using modern multi-channel equipment, the *Gradient array* is today the most popular 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.

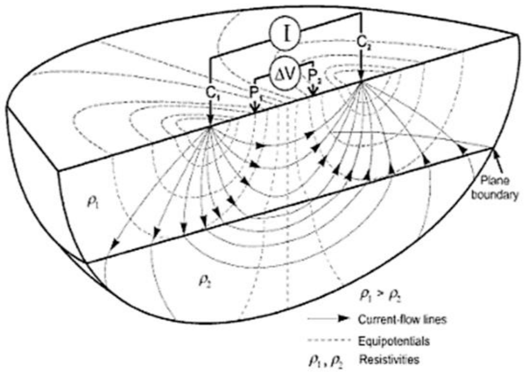

Figure 3 Test principle for ERT measurements (Knödel et al (2007)).

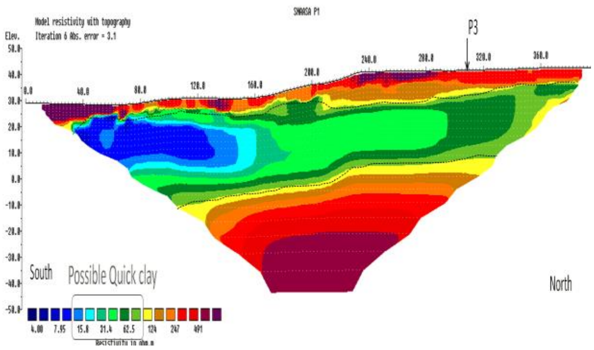

Figure 4 Resistivity profile from ERT measurements (NIFS-report 2015-126).

The obtained resolution is dependent 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 size of the influenced soil volume. It is however possible to measure a profile with several different electrode spacings 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.

ERT is a robust method that give results of high quality in most cases (see e.g. Rømoen et al (2010)). The measurements are however sensitive to objects in the influenced zone. This may be issues like electrical cables, tubes and other structures influencing the resistivity model.

3.4.3 Airborne measurements (AEM)

AEM (Airborne Electromagnetic measurements) are used to map the electrical resistivity of the ground in a larger area. Modern systems may have sufficient resolution to be used in hydrological and geotechnical applications. Recent studies show that it is possible to distinguish salt from leached clays with high resolution measurements, similar to what can be done by R-CPTU and ERT-measurements (e.g. Anschütz et al (2015)).

All AEM systems have in common that a magnetic field generated by the primary antenna induces current in the ground, which distributes downward and outwards from the source. The rate of change in the electro-magnetic field these currents produce, is recorded by a secondary coil. The antenna is usually lifted by a helicopter, see Figure 5. By inversion of the measured data points, the resistivity distribution in the ground can be modelled.

Figure 5 Equipment for AEM measurements (NIFS report 2015-126).

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 gradually gets poorer with depth. The lateral resolution is determined by the size of the soil volume where current is induced.

AEM data can be collected both over land and 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 are limited to a water depth of about 20 m. Up to 300 km flylines can be gathered daily, which corresponds to an area of about 30 km^2 with line spacing of 100 m. Urban areas cannot be covered by AEM-measurements, since it is not allowed to fly over human beings with a hanging object.

Table 2 Summary of investigation strategies for detection of quick and sensitive clays.

Project	Strategy
General – desk study: Introductory knowledge of brittle materials can be expected	The degree of detailing can be lower for simple projects compared to more complicated cases
Geophysical measurements: Overview of area and indication of leached clays	Geophysical measurements are placed to cover important parts of the area. **Use:** Soil stratification and planning of geotechnical borings **Note:** Methods indicate leached clays. This is not necessarily the same as brittle materials
Simple geotechnical soundings: Indication of brittle materials	Located for optimal use and verification of geophysical data. **Use:** Soil stratification, depth to bedrock and quick clay indication **Note:** 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	Located for optimal use of test results. **Use:** Determination of parameters and soil classification **Note:** These methods give a good, but not always safe, classification of brittle materials
Sampling: Failsafe detection of brittle materials	Parameter determination and soil classification. **Use:** Required in all projects according to the Eurocodes

	Note: Focus on areas where interpretation of in situ tests is uncertain.

4 STRATEGY FOR INTEGRATED SITE INVESTIGATIONS

Integration of geophysical and geotechnical methods has become more common 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 should be located with optimal cost efficiency. This approach may give large advantages when it comes to cost-efficient location of borings, but also more reliable interpretation of the ground conditions.

Resistivity measurements are well suited for mapping of the ground conditions in larger projects. With resistivity measurements, one may cover corridors for road or railway lines in relatively short time and with reasonable accuracy. As an outcome of this, one may detect critical areas with possible quick or sensitive clays, which need further geotechnical investigations for verification of the findings.

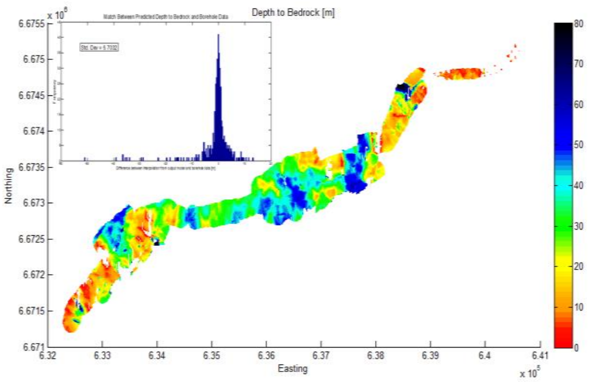

Figure 6 Map of AEM depth to rock compared to results from borings. The histogram shows a standard deviation between borings and AEM of 6 m (NIFS-report 2015-126).

Results from resistivity measurements can also be used 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.

A desk study should always be carried out ahead of a geophysical and geotechnical survey, possibly in combination with airborne measurements (AEM). This will help develop an optimal strategy for combination of AEM, ERT and introductory geotechnical borings. AEM appears to have roughly the same potential for detection of leached clays as ERT.

In urbanized areas, it may however be difficult or impossible to carry out resistivity measurements with sufficient quality. In this case, local downhole measurements using R-CPTU can be a practical solution in some cases, since this method is not particularly influenced by these obstructions.

5 CONCLUSIONS AND FINAL REMARKS

The conventional sounding methods (rotary weight, rotary pressure and total sounding) combined with sampling and laboratory testing will continue to be an important methodology for detection of brittle materials.

Cone penetration tests with pore pressure measurement (CPTU), alternatively with resistivity measurements (R-CPTU), has great potential for detection of brittle materials through combined recordings of cone resistance, sleeve friction and pore pressure. CPTU/R-CPTU, and possibly the electrical field vane test (EFVT), will provide natural follow-up investigations in strategically important locations, where the results will be used for supplementary classification and parameter determination.

When choosing these methods, one should have a more general perspective, based on the particular needs in each project. This may contain more than just detection of brittle materials. Both CPTU and R-CPTU enables a detailed mapping of the ground conditions with determination of soil stratification, soil type and mechanical parameters. Using 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.

Measurements of the total penetration force should always be carried out in a CPTU. This information can be used to detect layers of sensitive and quick clays by interpreting the variation in rod friction with depth. The measurement does not require any additional preparation time, so the added information comes for free.

There is generally good agreement between the measured resistivities from AEM, ERT and R-CPTU, particularly in homogenous soils. One major advantage of the resistivity measurements is the continuous information obtained about the soil layers. This is very important information for evaluation of stability problems, possible slide extension and run-out distance for remoulded and liquefied slide debris.

Vane test traditionally gives information about the in situ undrained shear strength (undisturbed and remoulded), and the sensitivity. The determination of the remoulded shear strength may give information about the presence of quick or sensitive clay. However, measurements with the manual vane equipment has to an unknown extent been influenced by rod friction. Modern systems, however, give possibilities for measurement of the friction, using an electro-mechanical unit for application of the torque, either at the top of the drillrods or down at the vane.

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. However, this method also represents 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.

It is recommended to summarize information from several boring methods for evaluating the presence of quick or sensitive clays. The results from all methods can then be evaluated at the same time. Both conventional soundings and CPTU/R-CPTU will require soil sampling and laboratory tests for verification.

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

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