Mapping of quick clay formations using geotechnical and geophysical methods

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Abstract Quick clay has been involved in most serious, large clay slides in Sweden, Norway, and Canada. This paper describes geotechnical and geophysical methods that can be used to locate and map the extent of quick clay formations. Surface resistivity measurements and four different sounding methods have been tested. The results have been compared with sensitivities determined using fall-cone tests. The investigation shows that there is a correlation between sensitivity and electrical resistivity, which can be used to discriminate between marine clays that have been leached sufficiently to possibly form quick clay and those for which the salt content remains sufficiently high to prevent this. Although the most reliable evaluation of the variation in sensitivity was obtained by the CPT with additional measurement of total penetration force, this investigation suggests that any sounding method that uses a constant rate of advance into the ground and in which the penetration force applied on the top of the rods is measured may be used for quick clay mapping.

Keywords Marine deposit · Sensitivity · Geophysical investigation · Electrical resistivity · Mapping

Introduction

Almost all landslides in clays in Sweden, Norway, and Canada with significant consequences can be designated as quick (or highly sensitive) clay slides (Viberg 1984). Examples of quick clay landslides in Scandinavia with serious consequences over the last 60 years include the Rissa, 1978, and Trögstad, 1967 slides in Norway, and the Surte, 1950, Göta, 1957, and Tuve, 1977 slides in Sweden. The location, time of occurrence, and size of quick clay slides are difficult to predict, which is unfortunate as large slides may cause great devastation. The extent of such slides is governed largely by the sensitivity of the clay to disturbance, with an additional but less important level of control imposed by the landslide geometry. As quick clay is such an important factor in the determination of stability, it is critically important to know if quick clay is present, and if so, to what extent, when a risk assessment is undertaken. This is the case for both general mapping of slide risks and for site-specific slope stability investigations.

The designation "quick clay" refers to a clay whose structure collapses completely upon remoulding, which causes an almost total loss of shear strength. The sensitivity, S_t, is the relation between the undisturbed and the fully remoulded undrained shear strength. Quick clay is defined in Sweden as a clay with a sensitivity of 50 or more and a fully remoulded shear strength of less than 0.4 kPa (Karlsson and Hansbo 1989). The latter value corresponds to a penetration of 20 mm by the 60 g cone with 60° tip angle in the fall-cone test.

In Canada, sensitive clays are defined as clays with a remoulded shear strength of less than 1.0 kPa and with a liquidity index of more than 1.2 (Robitaille et al. 2002). In Norway, quick clays are defined as clays with a remoulded shear strength of less than 0.5 kPa (Norwegian Geotechnical Society 1982).

Quick clay is formed naturally through geological processes. They are found in areas which were once glaciated during the Pleistocene epoch, mainly in northern Russia, Norway, Sweden, Canada, and Alaska (Brenner et al. 1981). These areas have been affected by isostatic uplift causing the deposits to be located above sea level. The exposed clay deposits have subsequently been subjected to leaching, whereby the ion concentration in the pore water has been changed. Rosenqvist (1946) showed that the properties of quick clays are due to leaching of the salt content in marine clays. Leaching is caused by infiltration of rain water, artesian water pressures in underlying permeable soil or rock, and by diffusion. These processes are slow, and as a result, quick clay is found more often in clay deposits with moderate thickness and less frequently in thick deposits. In thick deposits, quick clays may be found close to permeable layers and/or the ground surface. However, there are also quick clays that have been deposited in brackish and fresh water (Brenner et al. 1981). Through contact with organic substances in peat and other humus-rich soils, for example, the ion concentration in the pore water may change, and the clay may become quick (Söderblom 1974). The extents of these quick clays are often limited, however.

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

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

The aim of the investigation described here was to study different field investigation techniques for quick clay mapping and to evaluate their usefulness and suitability.

Quick clay formation

A clay consists of solid particles, and gas and/or liquid in the voids between the particles. The particles consist mainly of clay minerals, but other minerals may also be present. Clay minerals are so-called secondary minerals that have been formed by weathering of other silicates such as mica, amphibolites, and feldspar. The most common clay minerals are kaolinite, illite (hydrated mica), smectite (montmorillonite, saponite etc.), and chlorite. Illite is the dominatant clay mineral in Sweden. In southwestern Sweden, illite constitutes about 40–60% of the total clay fraction, quartz and feldspar about 15–25%, and the rest consists of kaolinite, chlorite, and maybe also some montmorillonite (Pusch 2005, personal communication). Most Norwegian clays are built up by the same minerals as per the Swedish clays, but the clay content is usually lower. Canadian clays contain more of the swelling mineral montmorillonite than the Scandinavian clays. Quick clays normally consist primarily of nonswelling minerals.

A clay mineral particle is made up solely of a clay mineral, and its grain size is normally not larger than 0.002 mm. During the last deglaciation, clay particles were sedimented where the water flow rate was low, initially at great distances from the ice front and then mainly in sea and lake bays as post-glacial sediments (Magnusson et al. 1963). Depending on the concentration of particles and the salt content in the water, among other factors, sediments were formed with different structures. A common characteristic for the clays in Sweden that were formed in this way is that they are built up by aggregates connected through links consisting of smaller particles. Pusch (1970) showed that the aggregates in clay deposited in a suspension with a high cation concentration (such as in seawater) are larger and denser than in clay deposited in fresh water. When these large aggregates sediment, they are arranged without any preferred orientation, resulting in a structure with a high void ratio. In a suspension with low cation content, each aggregate will consist of only a few particles, and these can thereby sediment into a denser and more uniform structure.

Leaching affects the forces between the particles, but normally not the flocculated structure (Brenner et al. 1981). On the other hand, leaching strongly affects the capability of the particles to re-flocculate after remoulding. If the salt is leached and the clay is remoulded, the clay particles cannot be connected into large aggregates again. The water holding capacity of the clay, which is reflected in the liquid limit, is thereby reduced. If the void ratio and the water content are high as a result of the original conditions at the deposition of the clay, remoulding will result in a clay "gruel" with small and separated particles and a liquid, low viscous consistency. Such a condition results in a reduction in remoulded shear strength and an increase in the sensitivity of the clay.

While a low salt content is a prerequisite for a high sensitivity, this is not always enough to make the clay quick, (Söderblom 1969; Bjerrum 1954 and Torrance 1978 for example). There are many marine clays with a low salt content that are not quick or particularly sensitive. One reason for this is that the composition of the ions in the pore water has a large influence on the possible formation of quick clay. Apart from the leaching, the ion composition depends also on a possible weathering of the clay minerals whereby ions can be released from the particles to the pore water. The larger portion of univalent ions of the total content of ions in the pore water, the better conditions for a high sensitivity. Torrance (1974) found that the salt (NaCl) content had to be reduced below 2 g/l (0.2%) before quick clay could be formed.

A case study from chemical perspective of quick clay in southwest Sweden has been presented by Andersson-Sköld et al. (2005). They observed that the upper limit of salinity that allows quick clay development in the Swedish-sensitive clays may be higher than the content found by Torrance (1974). They also found the Mg^{2+} concentration to be less than 100 mg/l when the clay is quick, in agreement with previous findings by Talme et al. (1966).

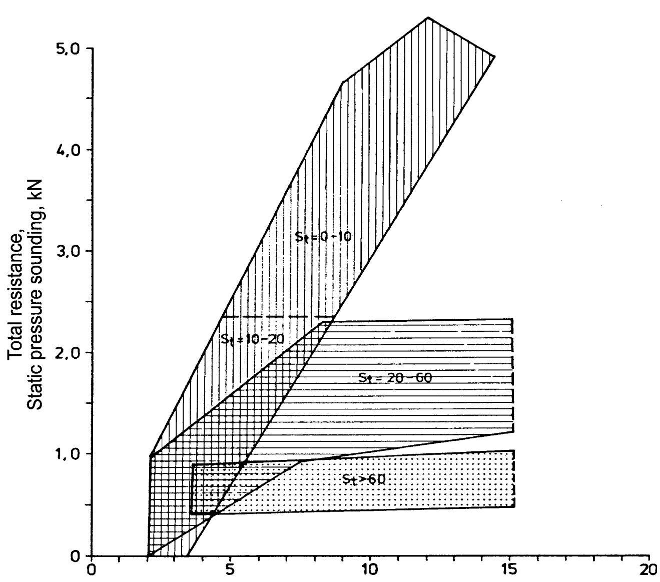


Fig. 1 Proposed areas in diagrams of penetration force versus depth for different ranges of sensitivity (after Möller and Bergdahl 1982)

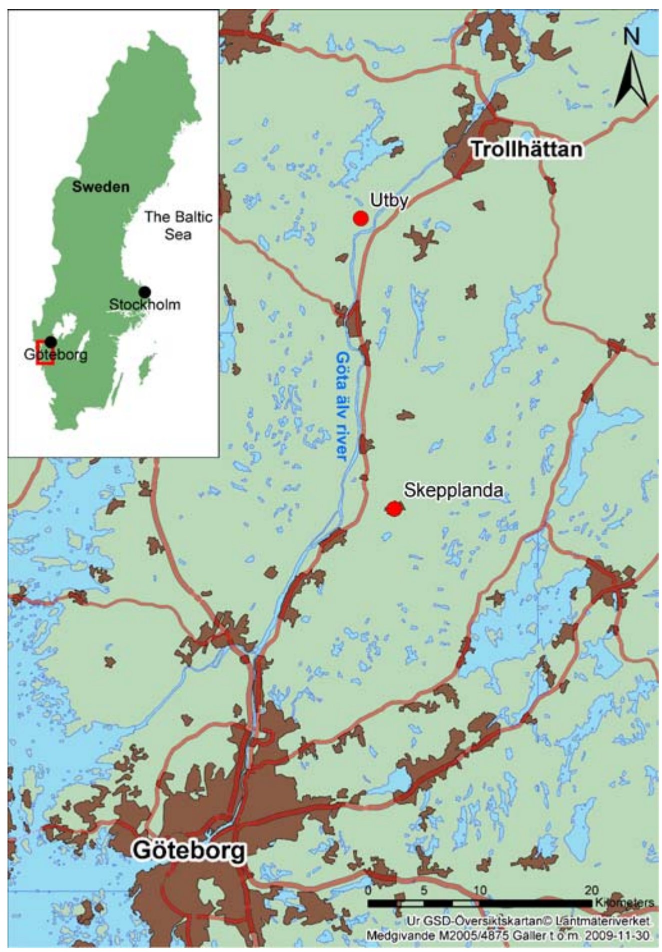


Fig. 2 Location of the test sites

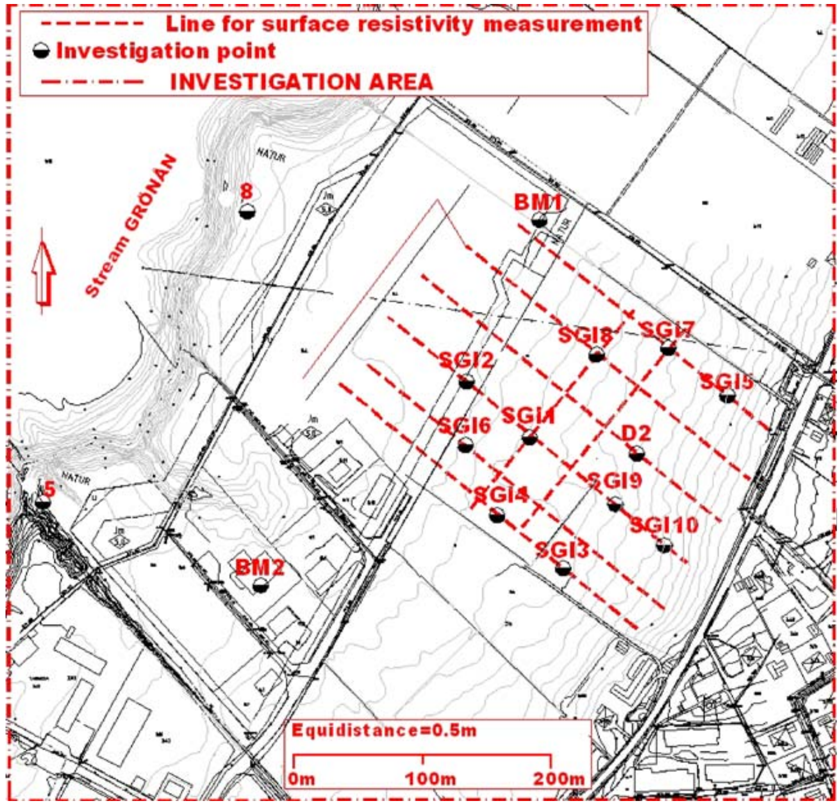


Fig. 3 Map showing the test site at Skepplanda. The position of geotechnical investigations and lines for resistivity measurements are indicated

In one of their studied sites, they found a continued decrease of undrained shear strength as the total ionic strength decreased, and Na^+ remained the dominant cation. This may be important because the experience from Drammen (Moum et al. 1971) and laboratory experiments with the Canadian quick clays (Torrance 1978) indicate that Ca^{2+} and Mg^{2+} ions at quite low concentrations can greatly affect remoulded behavior when they are the dominant cations present. There is an interplay between ion ratios and total ionic concentrations that complicates interpretation.

Clays with flocculated structures exhibit a higher void ratio and water content compared to sediments with oriented structures (Pusch 1970). Re-flocculation after remoulding is mostly not possible; this would lead to a significant reduction in the liquid limit, whereas the natural water content normally remains constant. A key characteristic of quick clay is that the water content is higher than the liquid limit. Data gathered by Larsson and Åhnberg (2003) show that the ratio between the water content and the liquid limit is normally higher than 1.1 in Swedish quick clays. The plastic limit decreases only slightly at leaching. A larger decrease in liquid limit than in plastic limit implies that the plasticity index, I_p, decreases. The sensitivity increases with increasing liquidity index, I_L. For the same type of clay, there is a fairly linear relation between the liquidity index and the logarithm of the sensitivity.

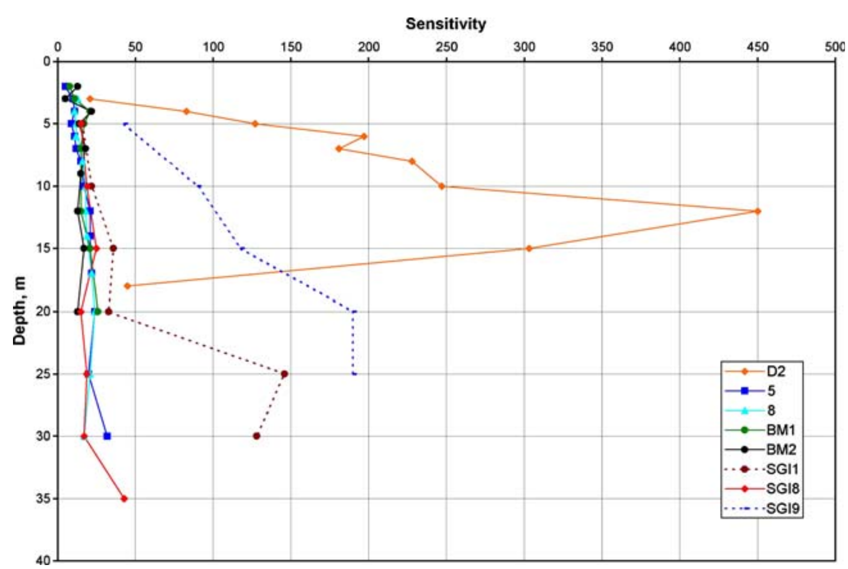


Fig. 4 Sensitivity values, determined by fall-cone tests, versus depth at different points at Skepplanda. See Fig. 3 for the locations of the investigation points

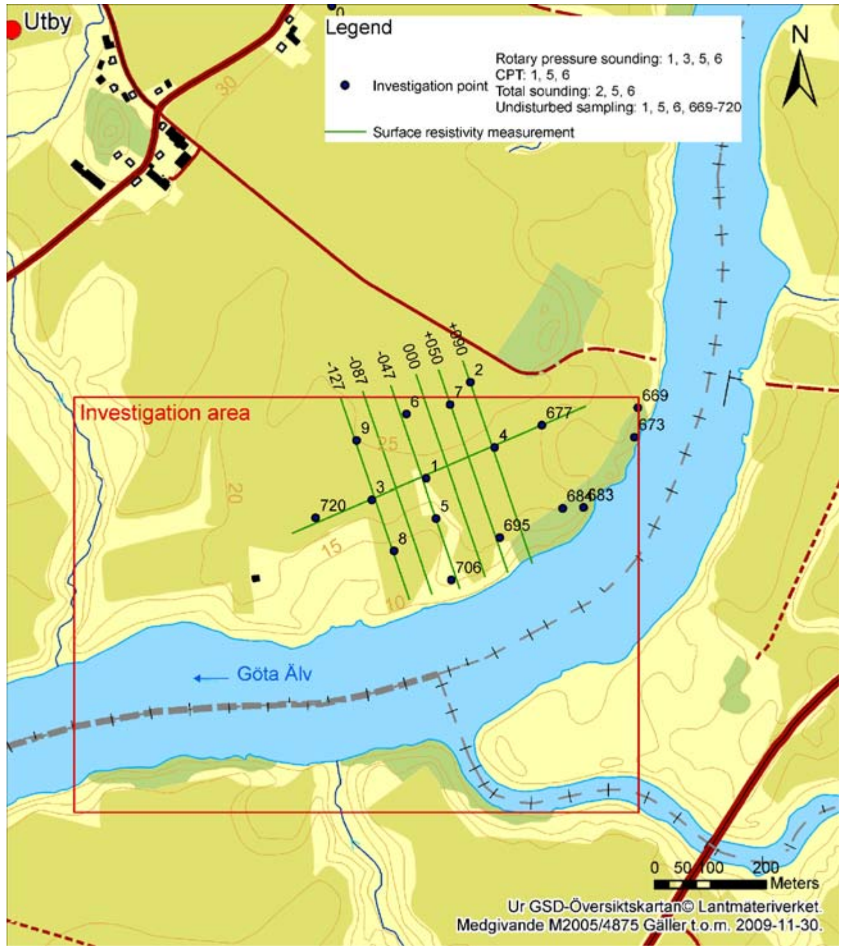


Fig. 5 Map showing the test site at Utby. The position of geotechnical investigations and lines for resistivity measurements are indicated

Methods used for mapping quick clays

Three different methods for quick clay mapping were used in this investigation. These three methods are described below.

1. *Soundings*

Certain correlations between sounding resistance and sensitivity have been previously noted. For example, Möller and Bergdahl (1982) and Rygg (1978) showed that the slope of the penetration resistance versus depth curve in clay can be linked to the sensitivity. Tentative charts for sounding resistances versus depth have been proposed. Möller and Bergdahl (1982) proposed for the static pressure sounding four different ranges of sensitivity of the static force–depth curve, which are shown in Fig. 1. They stated that if the inclination of the curve corresponds to an increase in penetration force less than 0.07 kN/m, the clay is likely to be highly sensitive or quick. To investigate this further, rotary pressure sounding, total sounding, static pressure sounding, and cone penetration tests were used in this investigation.

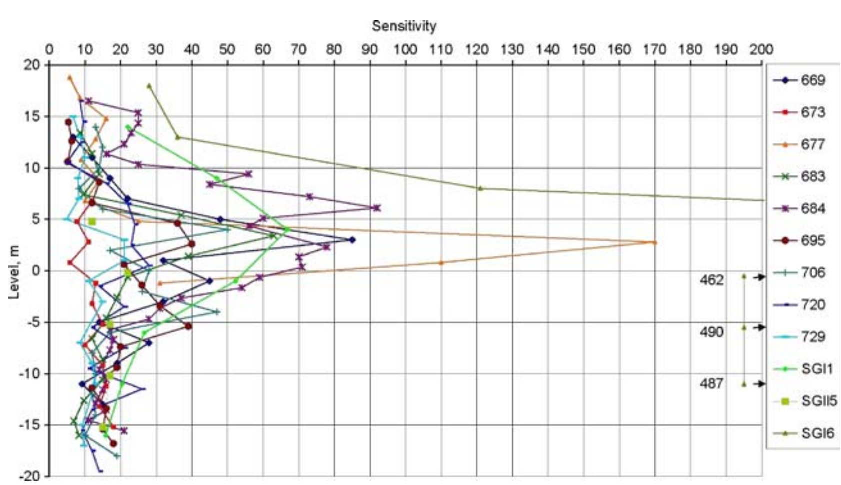
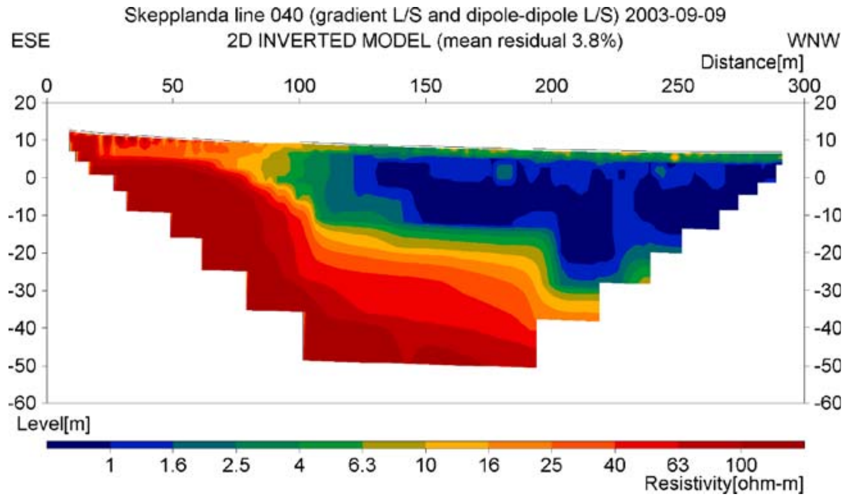


Fig. 6 Sensitivity, determined by fall-cone tests versus level at different points at Utby

Fig. 7 Resistivity sections for lines 040 (*upper picture*) and 120 (*lower picture*) for the Skepplanda test site. Grönån stream is situated around 200 m to the right of the images. The uppermost thin high resistivity layer corresponds to the dry crust, and bedrock is found somewhere in the red/dark red zones



Rotary pressure sounding is a Norwegian method that uses a twisted tip attached to sounding rods that are pushed down into the soil at a rate of 3±0.5 m/min while rotating at 25±5 rpm. The method is described by Statens vegvesen (1997).

The *total sounding method* was developed in Norway to penetrate all types of fills and soil layers as well as large blocks and bedrock, but it is also used to register significant strata in a soil profile and their relative stiffness. It uses a tip consisting of a specially designed drill bit with holes for a flushing medium. The drill bit is connected to hollow steel rods of the same type as those used for soil–rock drilling (such as geo-rods). In soft soil layers, the equipment is driven into the soil in the same way as in rotary pressure sounding, at a rate of 3±0.5 m/min while rotating at 25±5 rpm. The method is described by Statens vegvesen (1997).

Static pressure sounding was developed in Sweden. The original method has been modified, and it is now mostly used with the same type of twisted tip as used for weight sounding. The tip is pushed down into the soil at a constant rate of 20 mm/s, and the total pushing force is measured. If the maximum pushing force is reached, the system is rotated to achieve further penetration. The method is described by SGF (1996).

The cone penetration test consists of a probe connected to sounding rods that are advanced without rotation into the soil at a rate of 20 mm/s. The CPT measures tip resistance, sleeve friction, and penetration pore pressure. The total penetration force is normally not measured; however, this can be done fairly easily if the drill rig is equipped for any penetration test where the pushing force is measured in the rig itself (e.g., rotary pressure sounding, total sounding, or static pressure sounding). Using this additional information, a sounding is obtained in which both the friction at the tip and the friction along the perimeter of the equipment are obtained as functions of penetration depth. The CPT method is described by Lunne et al. (1997).

2. *Fall-cone test*

The usual way of estimating the remoulded shear strength in clay in Sweden is to use the fall-cone test. The method is described in the (Swedish Standard 02 71 25E 1991). The test can be used to determine both undisturbed and remoulded shear strength values, though the former determination requires undisturbed samples. A possible alternative to the time-consuming and costly undisturbed sampling is to determine the remoulded shear strength with fall-cone tests on remoulded samples and compare them to undisturbed shear strength values evaluated from field vane tests or CPTs.

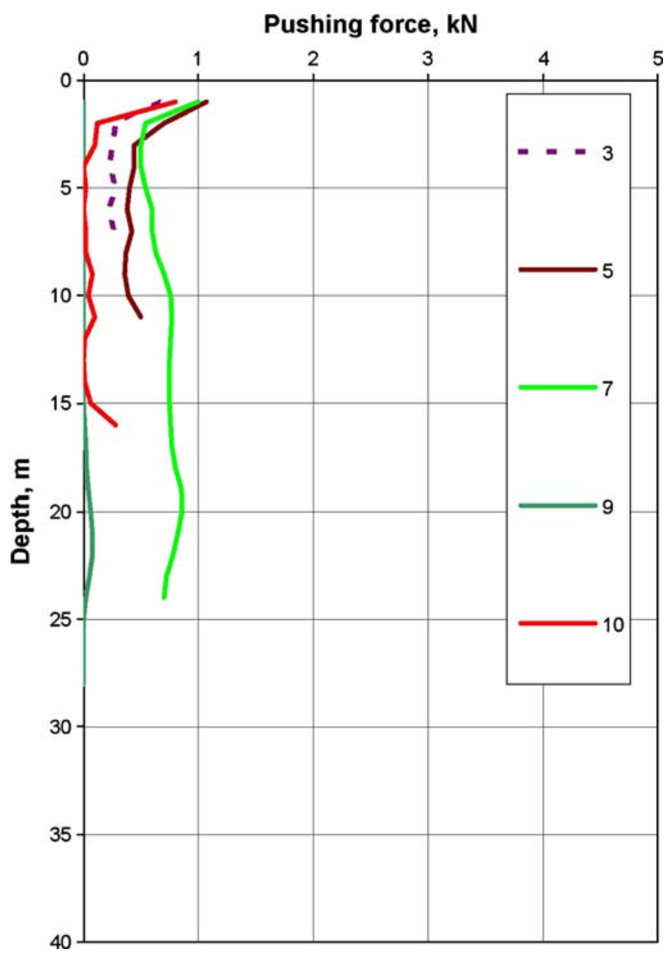


Fig. 8 Results from the static pressure soundings in the upper part of the slope at Skepplanda. Note that the curves have been smoothed as described in the text

3. *Surface resistivity measurements*

In marine clays that have been leached by fresh water, there is often a link between the salt content and the sensitivity of the soil, as well as between the salt content and the electrical resistivity of the soil (Söderblom 1969). However, a low salt content does not necessarily imply that the clay is quick but only that a precondition for this exists. Torrance (1974) found that the salt content has to be reduced below 2 g/l (0.2%) before quick clay can be formed. However, quick clay with a salinity (NaCl concentration) of 5.6 g/l was found by Andersson-Sköld et al. (2005). This value is very high compared to the upper boundary reported in Norwegian and Canadian quick clays. Andersson-Sköld et al. (2005) point out that such a difference is quite noteworthy and demands further investigation as to the possible reasons. A salinity below 0.2% is used in this report as a condition for quick clay occurrence.

The resistivity varies somewhat with the porosity of the soil, since it is mainly the pore water that is conductive (Penner 1965). Laboratory studies by Larsson (1975) and Hansbo and Larsson (1974) on a typical Swedish clay have shown that a content of 0.2% NaCl corresponds to a resistivity of between approximately 6 and 13 Ωm for the range of bulk densities of interest for quick clay formation in Swedish clays. Geophysical investigations made in mid-Norway by Solberg (2007) showed that quick clay has a slightly higher electrical resistivity (10–80 Ωm) than intact unleached clay (1–10 Ωm). The higher resistivity values obtained in that investigation, for quick clay occurrence, may be explained by the higher content of silt in Norwegian clays compared with Swedish ones.

The general principle for electrical surface resistivity measurements is to use a string of evenly spaced electrodes pushed into the ground surface along a measuring line. Overview descriptions of electrical surface resistivity surveying techniques are given by Dahlin (2001) and Auken et al (2006), for example. For each measurement, two electrodes are used to apply an electrical current into the ground, while the electrical potential is measured between one or several other pairs of electrodes, depending on whether the equipment has one or more measuring channels. The measured potentials depend on the magnitude of the current and of the conducting properties of the underlying soil. The depth and volume of the soil that influences a measurement are dependent on the spacing and position of the electrodes. By collecting measurements for a large number of electrode positions and spacings, a set of data is obtained that makes it possible to interpret and present an image of the electrical resistivity in the ground beneath the measuring line.

In the project reported here, the ABEM-Lund Imaging System multi-electrode data acquisition system was used for measuring

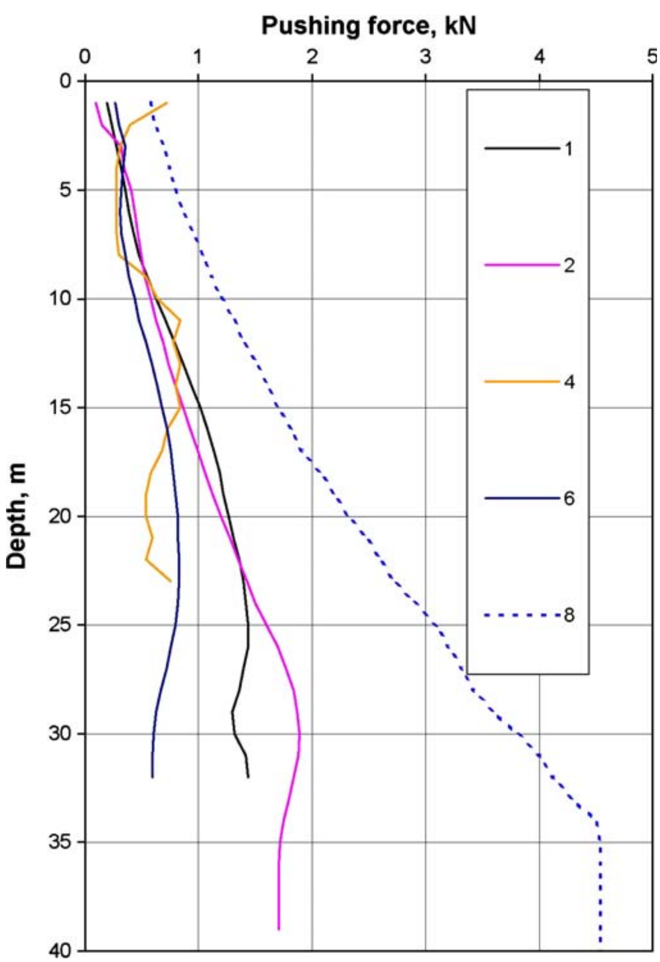


Fig. 9 Results from the static pressure soundings in the lower part of the slope at Skepplanda. Note that the curves have been smoothed as described in the text

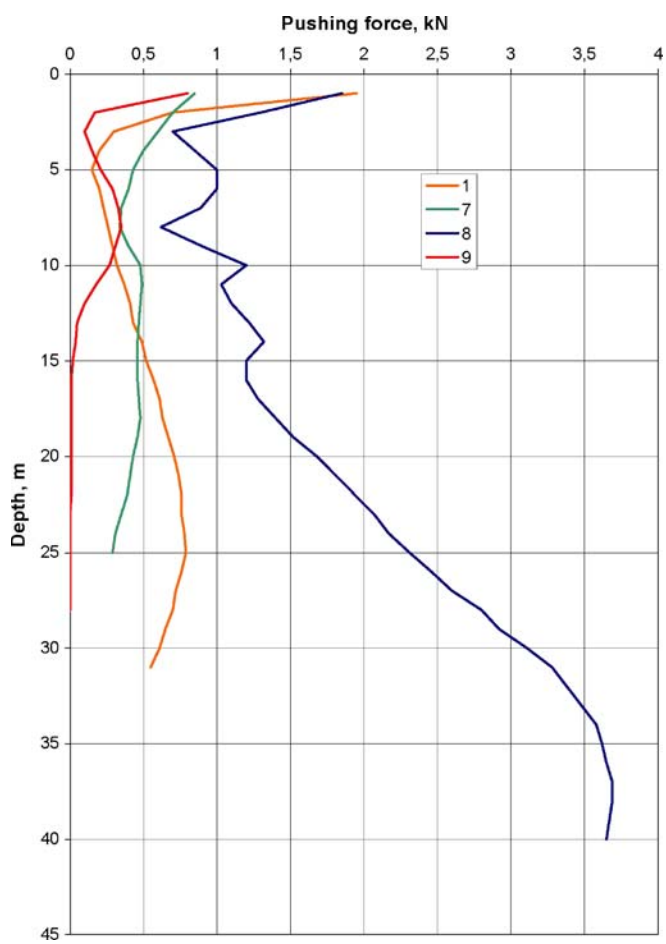


Fig. 10 Results from rotary pressure soundings at Skepplanda. Note that the curves have been smoothed as described in the text

resistivity with multiple gradient array (Dahlin and Zhou 2006). Electrode cables with a total of 81 electrodes in a full layout were used with a minimum electrode separation of 5 m, resulting in a total depth of investigation of around 75 m, as described by Leroux and Dahlin (2003). For interpretation, inverse numerical modeling (inversion) was used to establish two-dimensional models (cross-sections) of the underlying soil. A finite element forward modeling routine was used to compare the measured values with those that theoretically could be obtained for a model of the ground, and the resistivity distribution of the model was adjusted iteratively to obtain the best fit to the measured values. In this case, the Res2Dinv program was used to carry out robust (L1-norm) inversion (Loke et al. 2003).

The quality of the measured data depends greatly on the contact between the electrodes and the ground. Natural ground, homogeneous clay profiles, thin crusts, and fairly wet conditions are thus beneficial factors for the measurements, whereas fills, pavements, overlying layers of coarse soils with low ground water tables, and thick, dry crusts are factors that reduce the quality of the measurements. Buried electrically conductive objects in the ground such as cables, pipes, piles, and walls may distort the results and give artefacts in the interpreted models. Strongly inhomogeneous ground, as well as a highly irregular ground surface, can complicate the interpretation of the data unless a full 3D investigation with high resolution is used.

Test sites

Two test sites, Utby and Skepplanda in southwest Sweden, both of which have a known occurrence of quick clay, were used for the evaluation of the different mapping methods (Fig. 2). The investigation program was designed to include both areas with quick clay as well as areas without such formations to establish the limits of the quick clay formations. There was prior information in both areas that quick clay was present, although it was not sufficient to provide more than a rough idea of its extent. In both sites, the clays have been deposited by sedimentation in a marine environment after the latest glaciation, which ended around 10,000 years ago. The highest postglacial marine shoreline in the area is found about 110 to 120 m above present sea level. A full description of the test sites is given by Rankka et al. (2005).

Skepplanda

The Skepplanda test site is located about 40 km north of Göteborg in a side valley to the Göta Älv valley. The terrain slopes gently with a height difference of 10 m over a distance of about 500 m, toward a steeper slope down to a small stream, *Grönån* (Fig. 3). The soil consists of soft marine clay below a relatively thin, dry crust. The thickness of the clay layer increases from very thin layers at the upper border of the investigation area to about 40 m at the center of the area. The exact depths of the clay layers in the lower part of the area are unknown but are probably large. In the area investigated, and probably over the whole area, there is a layer

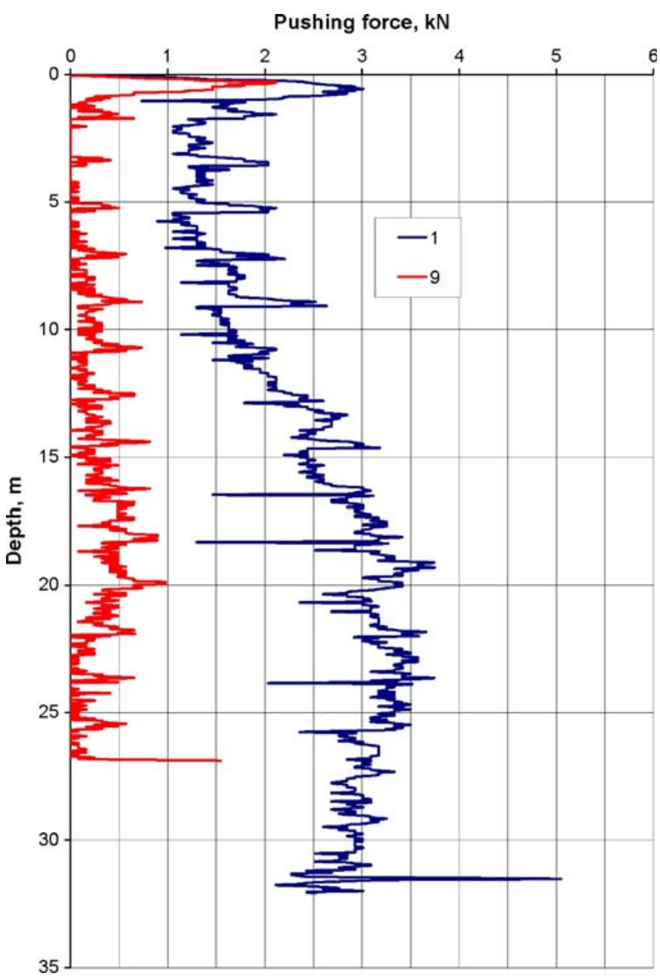


Fig. 11 Results from total soundings at Skepplanda

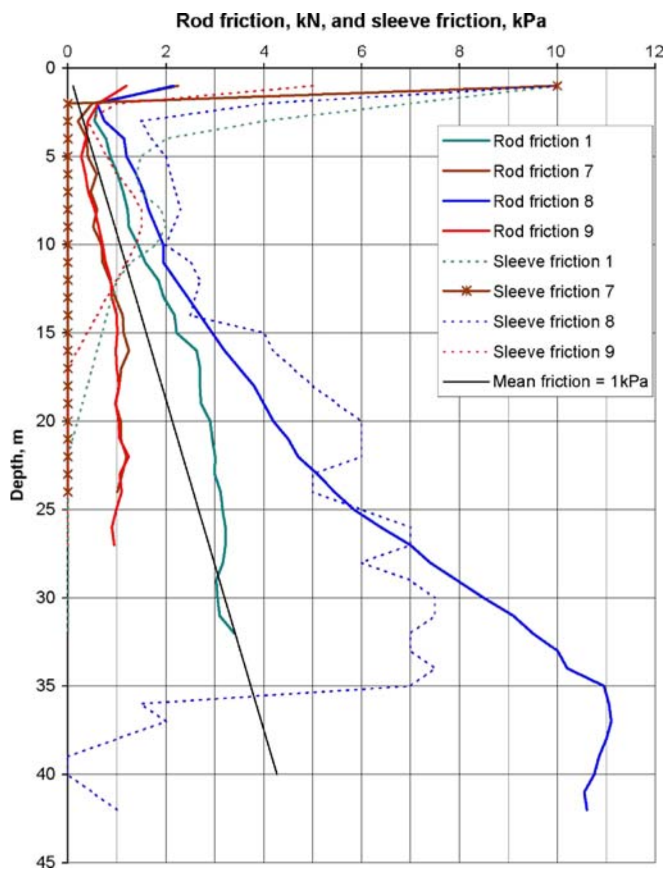


Fig. 12 Results from the CPTs at Skepplanda in terms of rod friction and sleeve friction versus depth. Note that the curves have been smoothed as described in the text

of till between the clay and the bedrock. Its thickness varies between almost zero and a couple of meters, but can generally be assumed to be about 1 m. The layer is permeable, and the water pressures in this layer are artesian because of the sloping terrain and sloping underlying bedrock. The free groundwater level is located in the dry crust and varies seasonally from the ground surface to about 1 m below. Because of the artesian water pressure in the bottom layers, there is an upward gradient and pore water flow in the soil mass.

The undrained shear strength of the soft marine clay is about 5 kPa per meter depth right below the thin dry crust and increases by about 1 kPa per meter depth in the upper half part of the area. Further down the slope, the dry crust is more pronounced, and the undrained shear strength is more or less constant at around 12 kPa down to 10 m depth, and then increases by about 0.8 kPa per meter depth.

The resistivity measurements were performed in six lines about 300 m long from just below a road in the upper part of the investigation area to well below the central parts (Fig. 3). Two cross lines of the same length running on opposite sides of the center of the first six lines were also measured. Different geotechnical investigations have been performed at 15 points (Fig. 3). Static pressure soundings were performed at points SGI1–SGI10, rotary pressure soundings at SGI1, SGI7, SGI8, and SGI9, total soundings at SGI1 and SGI9, CPTs at points SGI1, SGI7, SGI8, and SGI9, and undisturbed sampling was performed at points 5, 8, D2, BM1, BM2, SGI1, SGI8, SGI 9 (Fig. 3).

Results from determinations of sensitivity by fall-cone tests show that quick clays are confined to the upper part of the area and that clay with sensitivity values of several hundreds is found at point D2 in the upper part (Fig. 4). It should also be noted that the clay tends to be more quick in deeper layers at point SGI9, which is located somewhat lower down in the area and that quick clay is found only in the bottom layers at point SGI1, which is located even further down toward the Grönån stream.

Utby

The test site at Utby is located on the western bank of the *Göta Älv* river about 50 km north of Göteborg (Fig. 2). While most of the investigation area is essentially flat or very gently sloping toward the river, steep slopes are found adjacent to the river or in the ravines at its tributaries (Fig. 5). The river makes a sharp turn around a couple of small outcropping hillocks just upstream of the site. At the test site, there is a depression in its south western part reaching about 200 m in from the riverbank as a result of an earlier landslide.

The clay in the area is marine clay with a dry crust of about 1 m. The clay is assumed to be resting on a layer of till on top of bedrock. The depth to bedrock is not known, but it is more than 20–40 m. Investigations have shown that the undrained shear strength is approximately 20 kPa just below the level of the plateau

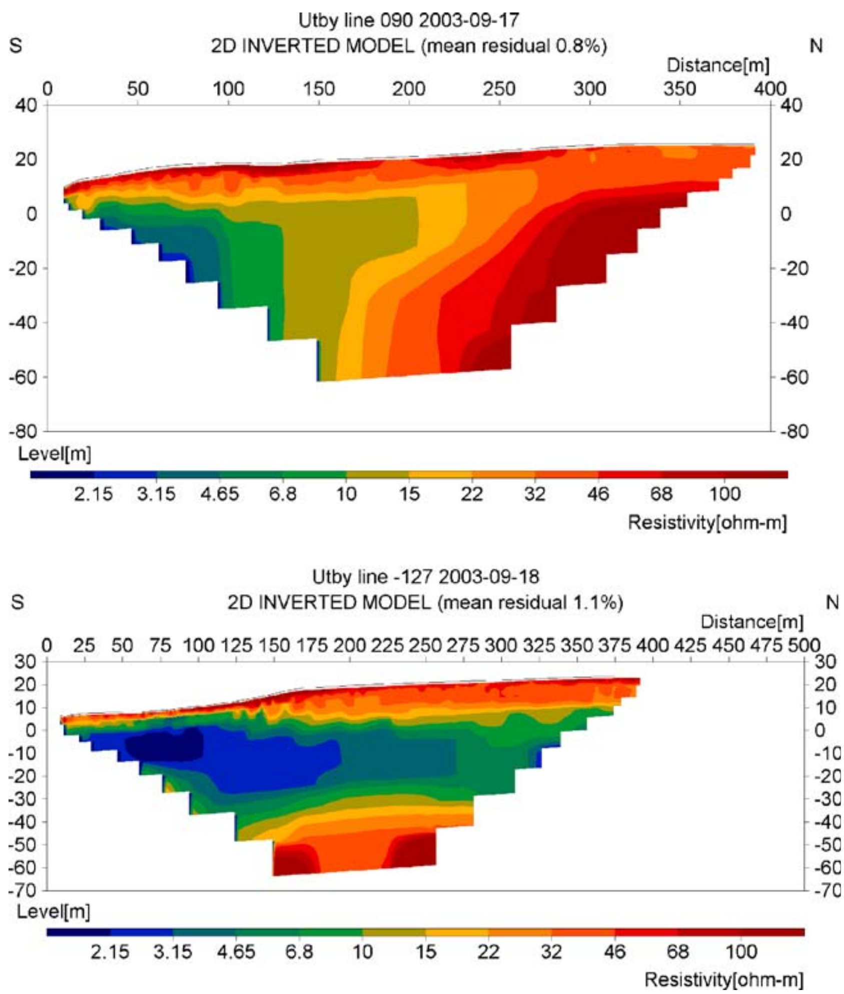


Fig. 13 Resistivity sections for lines 090 (*upper picture*) and 127 (*lower picture*) at test site Utby. The Göta älv river is situated to the left of the images. The uppermost thin high resistivity layer corresponds to the dry crust

(level +15) and then increases by 1 kPa per meter depth. The pore pressure measurements performed in earlier investigations indicate free groundwater levels close to the ground surface. At the upper plateau, there is a downward gradient with less than hydrostatic pore pressures. At the riverbanks, artesian water pressures somewhat higher than hydrostatic pore pressures exist. Considering the topography, the pore pressures below the river may be assumed to be even more artesian.

The resistivity measurements were performed in six parallel lines about 400 m long running perpendicular to the river and starting just above the crest of the steep slope at the riverbank. A crossline approximately 500 m long running parallel to the river and at the center of the first six lines was also measured. The positions of the lines are shown in Fig. 5.

Different geotechnical investigations have been performed at 17 points (Fig. 5). Static pressure soundings were performed at points 1–9, rotary pressure soundings were performed at points 1, 3, 5, and 6, total soundings at points 2, 5, and 6, CPTs at points 1, 5, and 6, and undisturbed sampling were performed at points 1, 5, and 669–720.

Results from fall-cone tests show that clay with high sensitivity is found in the northeastern part of the area (points 1, 6, 669, 677, 683, and 684), whereas the clay in the southwestern part has lower values (Fig. 6). It was also found that the thickness of the highly sensitive layers generally increases with distance from the river and toward areas with lower thickness of the clay layers.

Results of the determination of quick clay extent

Skepplanda

The *surface resistivity measurement* in Skepplanda showed high resistivity values in the upper part of the area, whereas gradually lower resistivity was found further down toward the river (Fig. 7). Lower resistivity values correspond to a higher salt content, and the resistivity sections indicate that leaching occurs from the bottom upwards, which should correspond to the artesian groundwater conditions. A detailed data report concerning the geophysical resistivity measurements included in the present study has been presented by Leroux and Dahlin (2003).

The results of the *static pressure soundings* are given in Fig. 8 (upper part of investigations area) and in Fig. 9 (lower part of the area). They confirmed the general picture in that the inclination of the curve for sounding resistance versus depth was almost vertical or even negative in the depth intervals with quick clay. At points 9 and 10 (for the location, see Fig. 3), where there is quick clay almost throughout the profile, the equipment sank under its own weight for large depth intervals. In those parts where the sensitivity was lower, it was observed that the sounding resistance

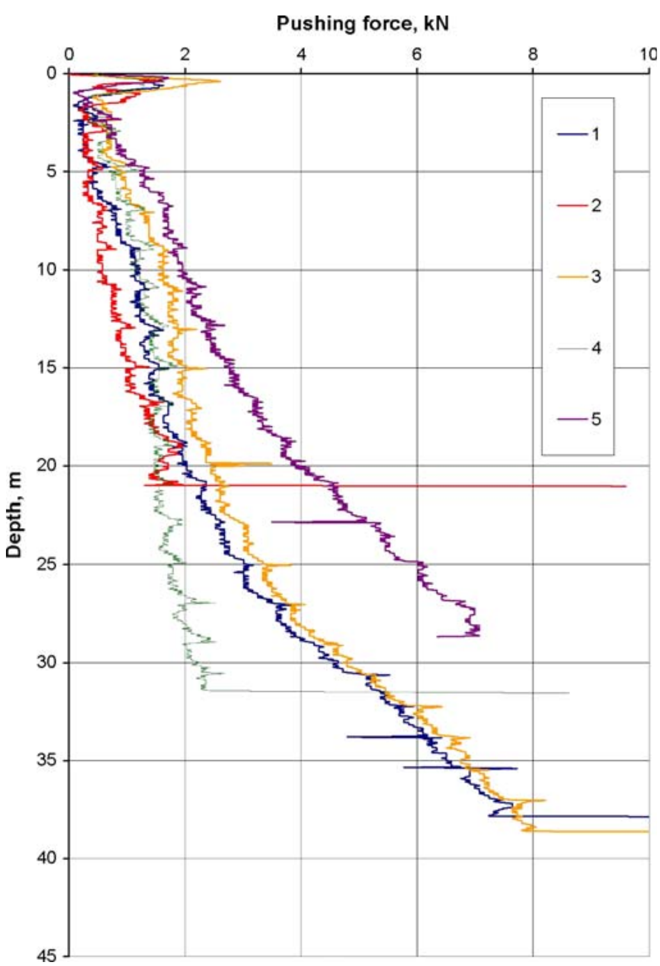


Fig. 14 Results from the static pressure soundings in points 1–5 at Utby. For the location of investigation points see Fig. 5

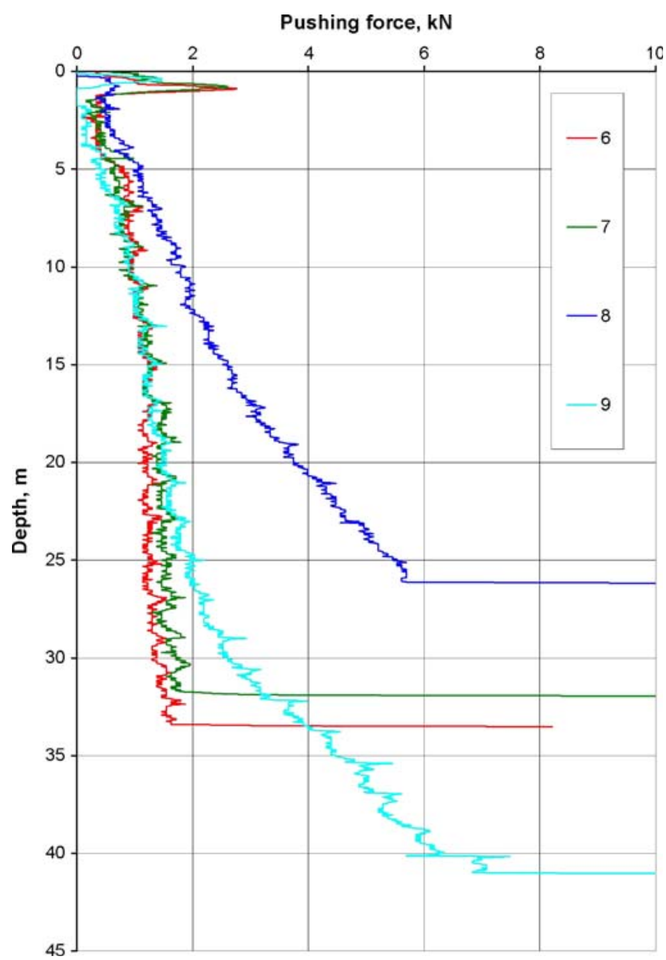


Fig. 15 Results from the static pressure soundings in points 6–9 at Utby. For the location of investigation points see Fig. 5

increased each time the penetration was stopped to add new rods and raise the pushing yoke. It then took almost a meter of further penetration before all the effects of the stop were erased. The results of the static pressure soundings are presented as smoothed curves after removal of these stop effect. Even a first glance of the results provides a good relative picture of the distribution of the sensitivity in the soil mass. From the results, it can be observed that in the upper part of the slope (Fig. 8), each profile is quick throughout and that further down (Fig. 9) there is only a zone at depths of 20 m or more that is quick. This zone follows the bottom contour and decreases in thickness with distance from the upper part of the investigation area and increasing thickness of the clay layer.

The results from *rotary pressure sounding* (Fig. 10) and *total soundings* (Fig. 11) show approximately the same picture as the static sounding test, though the rotary pressure soundings show somewhat less detail. Both types of equipment sank under their own weight for part of the profile in the most sensitive clay.

For the *CPTs*, the results have been corrected by subtracting the measured tip resistance from the total penetration force and adding the weight of the rods. The curves have also been smoothed to remove the enhanced friction due to temporary stops in the penetration. The rod friction is generally higher than for the other sounding methods, which can be attributed to the considerably lower remoulding by the tip. The pattern of the rod friction versus depth is the same as for the other test methods, but the curves are not quite as steep (Fig. 12).

In Fig. 12, a guiding line corresponding to an average rod friction of 1 kPa has been inserted. An inclination steeper than this line indicates that the clay is highly sensitive and probably quick, and parts in which the curves are vertical or almost vertical indicate quick or highly quick clays. The general picture is verified by the measured sleeve friction, which is zero or almost zero in the parts with highly quick clays and generally less than 2 kPa in the parts with highly sensitive to quick clays. When judging the absolute values of the sleeve friction, it should be considered that these may be expected to be considerably higher than the completely remoulded shear strength and that the measuring accuracy is normally ±2 kPa at best. However, the pattern should match the estimated sensitivity from the total rod friction, which it clearly does here. The results of the CPTs also indicate that there is denser clay at the bottom of the clay profiles, with embedded thin silt layers at the very bottom. The quick clay in the deeper clay profiles is located mainly in this layer.

Utby

The surface *resistivity measurements* showed high values in the northeastern part of the area, whereas gradually lower resistivity was found further down toward the river and southwest. The resistivity sections indicate that leaching has occurred from both percolation of water from the ground surface and diffusion from draining layers at the top and bottom, which corresponds to the groundwater conditions (Fig. 13).

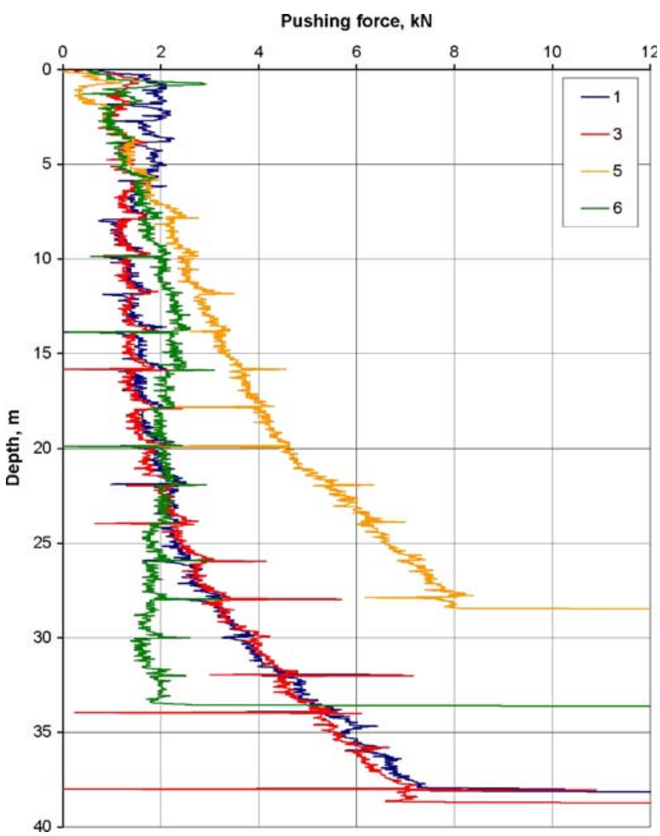


Fig. 16 Results from the rotary pressure soundings in points 6–9 at Utby. For the location of investigation points see Fig. 5

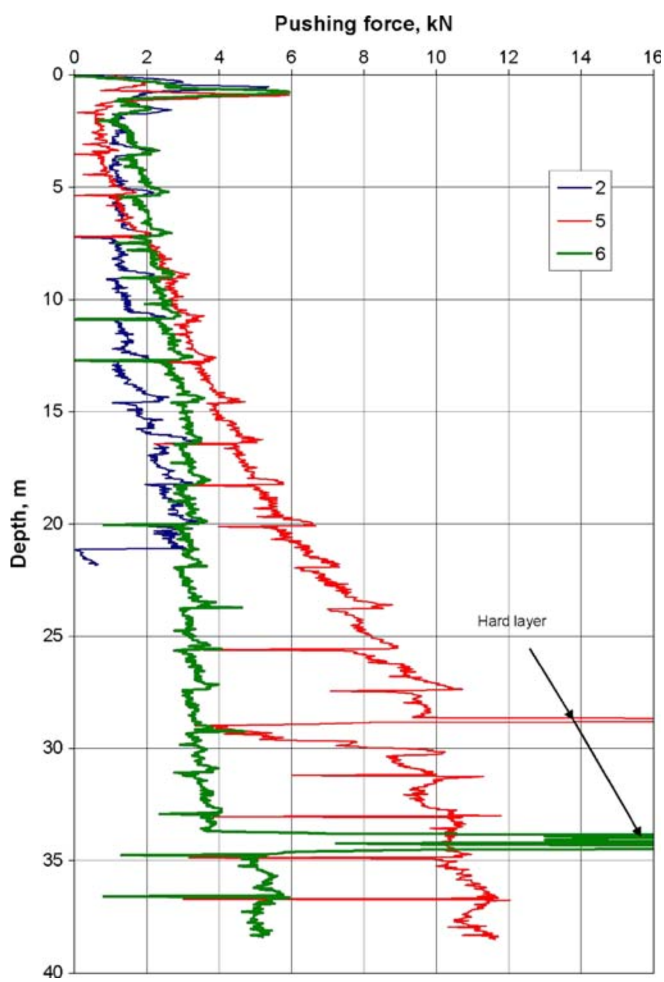


Fig. 17 Results from the total pressure soundings in points 6–9 at Utby. For the location of investigation points see Fig. 5

The results of the *static pressure soundings* (see Figs. 14 and 15) show increased resistances after each stop in the penetration and almost vertical penetration force vs. depth curves in the parts with quick clays. Note that these graphs have not been smoothed as was the case for the results given for the test site Skepplanda. No quick clay was indicated at points 5 and 8 in the southwestern part of the area, whereas such parts with increasing thickness toward the northeast could be seen at the other points. In this case, the crest and upper non-quick layers were thick enough to prevent the equipment from sinking under its own weight. Below this part, the layer of quick clay is limited to a certain depth interval except for points 6 and 7, in which quick clay appears to occur throughout the penetrated depth. At point 6, a hard layer was hit at around 34 m depth, whereas it is uncertain whether this layer or bedrock was reached at point 7.

The results from the *rotary pressure soundings* (Fig. 16) and the *total soundings* (Fig. 17) yielded approximately the same picture as the static pressure soundings. However, the inclination of the penetration force vs. depth curve in the rotary pressure sounding became negative for a large part of the profile at point 6, where the most sensitive clay was found.

The evaluated rod friction and the measured sleeve friction in the *CPTs* are shown in Fig. 18. The pattern of the rod friction versus depth is the same as for the other test methods, and the measured trends for the rod friction are supported by the measured sleeve friction.

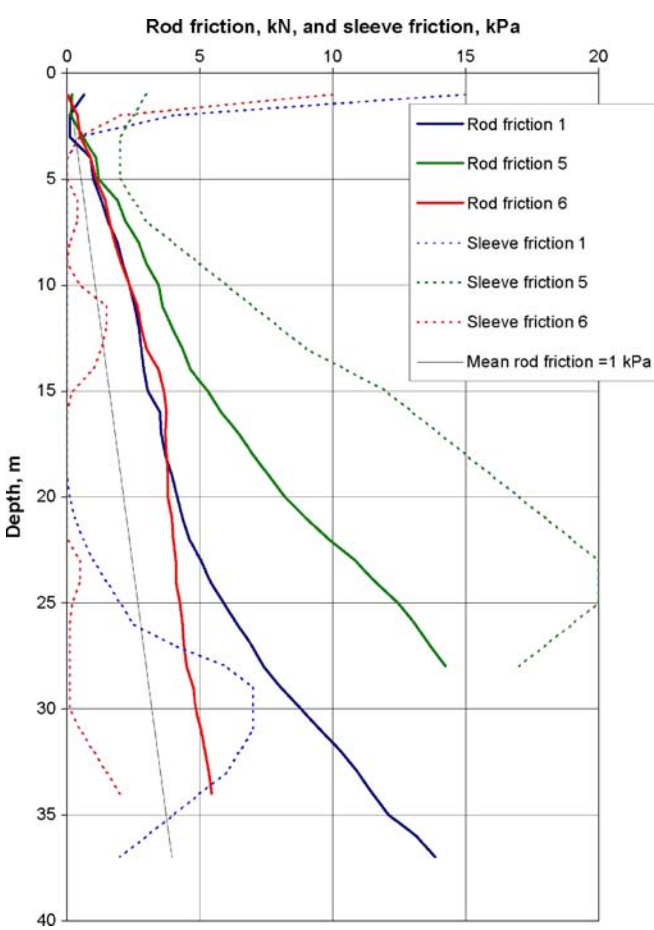


Fig. 18 Results from the CPTs at Utby in terms of rod friction and sleeve friction versus depth

Discussion

The study has shown that there is a general correlation between the slope of the pushing force to depth curve and the sensitivity of the soil at the same depth (Fig. 19a–d). However, since there is no direct connection between pushing force and sensitivity, there is a large variation in sensitivity for any given slope of the sounding curves, except for the very flattest. The correlations can therefore be used mainly for a rough division of the soil into sensitivity classes. No precise rules can be given for the way in which this should be done because the correlation is only indirect and depends on soil type, equipment, and test performance.

The stroke in each pushing operation used in sounding methods should preferably be at least 2 m in order to enable separation of the thixotropic effects that occur each time the operation is interrupted for the addition of new rods. It should be observed that the variations in total penetration force are not related to rod friction alone, but significant changes in tip resistance may distort the general picture. Thus, the large change in tip resistance after passing through the stiffest part of the dry crust makes it impossible to draw any conclusions about the sensitivity in the layer just below the crust. The same problem occurs when passing embedded stiffer layers in the soil profile. An almost constant or decreasing penetration force may also be a result of the tip entering soil layers with continuously decreasing plasticity, such as varved and silty bottom layers, in which also the tip resistance decreases.

Another source of error is that the rod friction away from the tip may change significantly. This can occur if high friction caused by coarse soil in the crust or any other large object is released when these objects are dislodged. It can also be caused by a wobbling motion of the rods leading to enlargement of the drill hole and local gaps between the rods and the soil. Furthermore, any change in the rod diameter in the string of drill rods will create a change in the pattern of the penetration curve and cannot be permitted.

These potential errors can be avoided by using CPTs with the additional measurement of the total penetration force. Provided that a sensitive probe is used, the rod friction can be separated and checked by using the readings of sleeve friction at the very tip. The fact that there is no direct correlation between the rod friction (or sleeve friction) and the sensitivity still remains. On the other hand, CPTs provide a fairly accurate determination of the undrained shear strength, which together with determinations of liquid limit and remoulded shear strength on samples, can be used to calculate the sensitivity. The latter two determinations do not require undisturbed samples.

The correlations between sensitivity measured by fall-cone tests and resistivity estimated from inverse numerical modeling are given in Fig. 20. It should be noted that the sensitivity and resistivity values arise from measurements at widely different scales, with small-scale laboratory determinations of the former, whereas the latter are derived from measurements that integrate the electrical properties over large volumes that increase with the depth below ground surface. Nevertheless, correlations are evident, and as can be seen, resistivity values of less than 5 Ωm mean that the salt content is too high to allow quick clay formation. It can also be seen that a high resistivity value and low salt content does not automatically entail that the clay is sensitive.

Results from surface resistivity measurements and geotechnical investigations made at the test sites in Skepplanda and Utby are presented as quasi three-dimensional pictures in

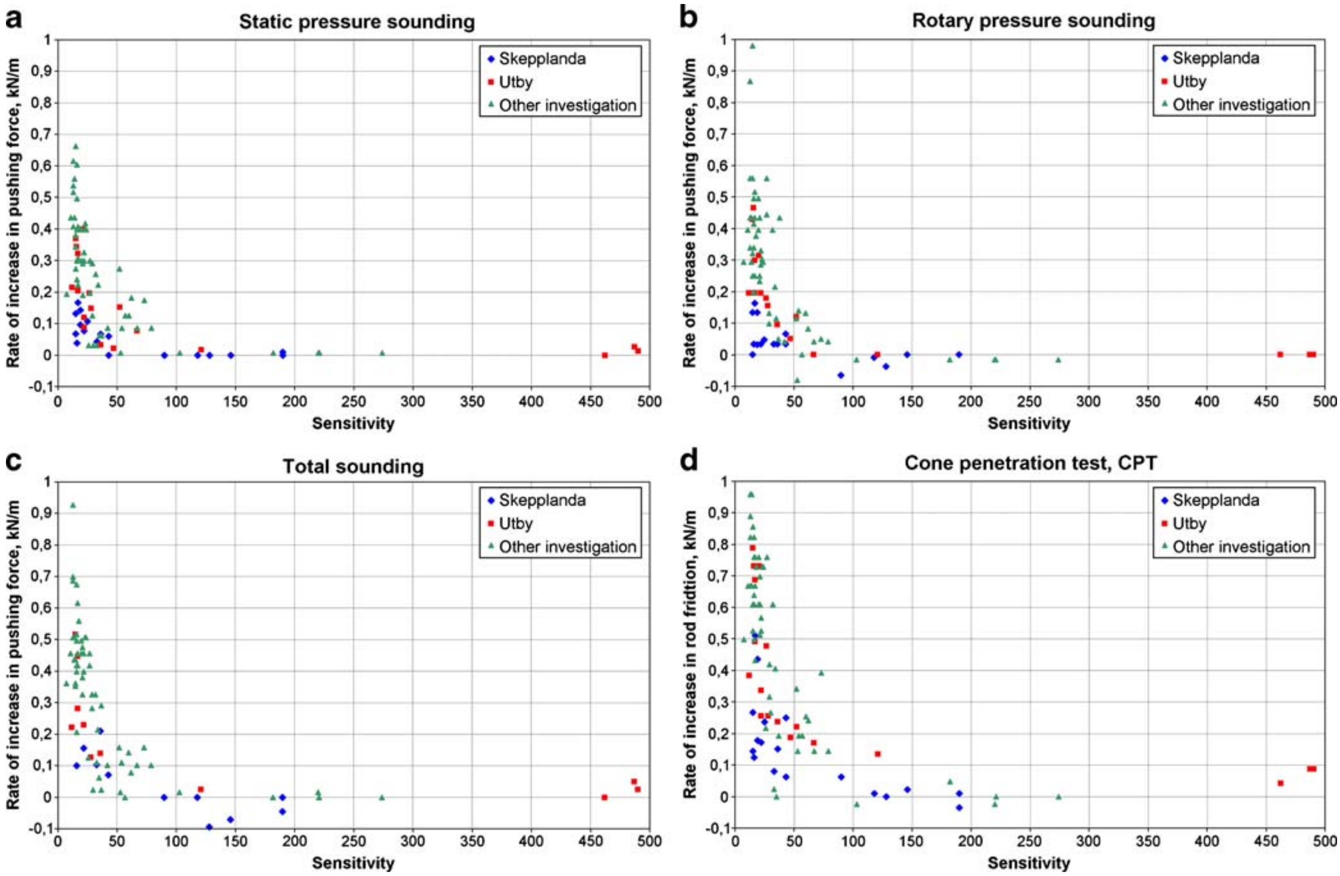


Fig. 19 **a** The relationship between *static pressure* sounding resistance and sensitivity for the two sites. **b** The relationship between *rotary pressure* sounding resistance and sensitivity for the two sites. **C** The relationship between *total* sounding resistance and sensitivity for the two sites. **d** The relationship between *corrected rod friction* (from CPT) and sensitivity for the two sites

Figs. 21 and 22. The resistivity measurements provide continuous two-dimensional images of the soil in the measured sections. These sections can be combined, using computer programs, with the cross-sections into a quasi three-dimensional picture of the whole investigated soil mass. The geotechnical investigations are, though, performed at single points and provide profiles only at these points. There are no corresponding programs available on the market to create a three-dimensional picture based on these kinds of investigations, but a manual process can be used provided that there are sufficient investigation points. In the actual cases, there are several test points in each limited area, and the points have been located to enable such modeling. When creating the geotechnical models, the same views have been selected as those that were found to give the best illustration of the resistivity distribution. A direct comparison between the models can thereby be made.

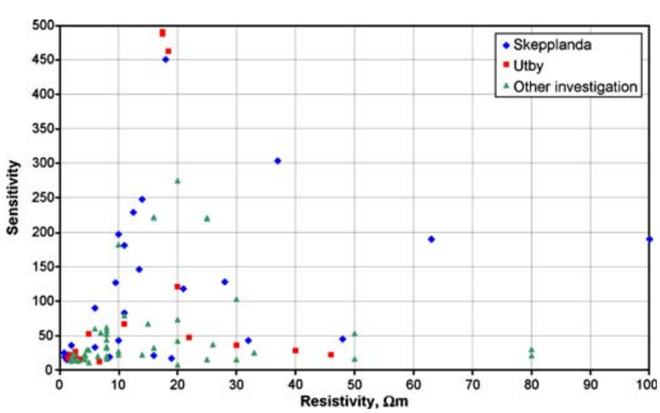


Fig. 20 Graph showing the relationship between resistivity and sensitivity

In the resistivity measurements, green and blue colors represent soils with resistivity values below 6.3 Ωm, which corresponds to clays that have not been leached enough to possibly form quick clay. The yellow color represents soils with resistivity values between 6.3 and 16 Ωm (probable prerequisites for quick clay), while the red color represents soils with resistivity values above 16 Ωm which are sufficiently leached soil for quick clay formation. However, the red color may also indicate dry crust, bedrock, or other firm material.

In the geotechnical model, the soil has been divided into four sensitivity classes. The blue color represents normal sensitivity, which for the clays in western Sweden is up to about 30. The green color represents highly sensitive but not quick clays with sensitivity values in the range of 30–50. The yellow color represents quick clays with sensitivities above 50, and the red color shows highly quick clays with sensitivity values of several hundred and sometimes nonmeasurable levels. The criterion that the remoulded shear strength must be less than 0.4 kPa in quick clay has also been checked.

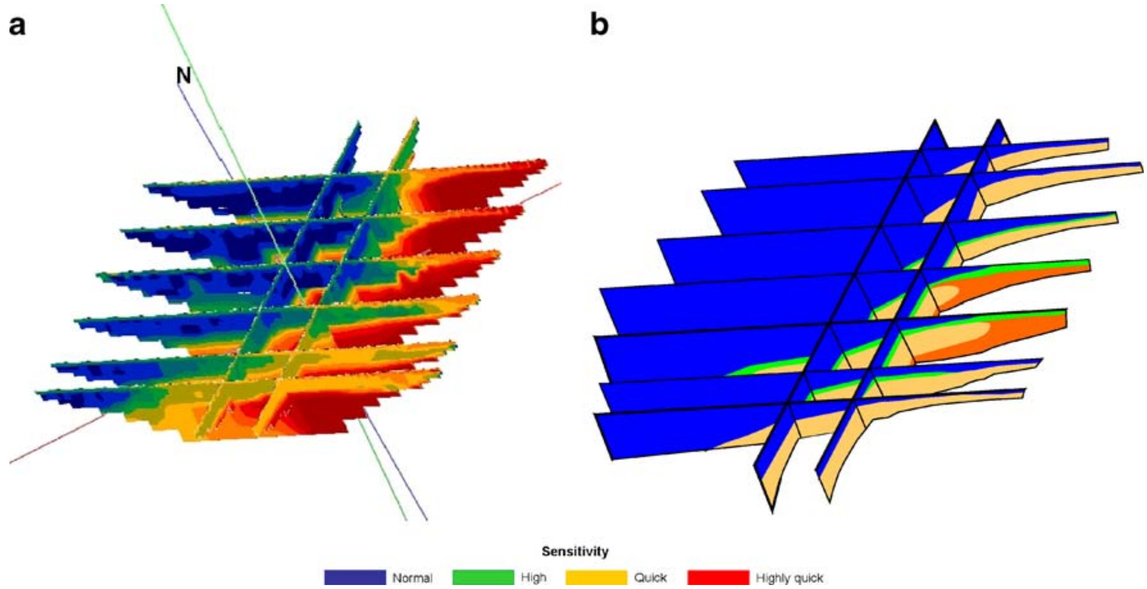


Fig. 21 Quasi 3-dimensional models of the soil at Skepplanda. (**a**) Resistivity model, (**b**) Geotechnical model

From the results obtained in the Skepplanda test site, it can be observed how the results of the two models match with quick clay found in the significantly leached parts. It can also be observed that clay with normal sensitivity is found where the salt content remains high. The only discrepancy is the zone for the dry crust and the thin weathered zone at the top, where the resistivity is high but the clay is non-quick, but this is to be expected for other reasons, as previously explained. It can also be observed how the thickness of the clay layers, the permeable layer below the clay, and the artesian water pressures have affected the leaching process and quick clay formation. The dark red zones in the lower right part of the resistivity presentation show the underlying bedrock.

At the Utby site, there is a very good correlation between the two models, except for the depths of the profiles. All the geotechnical investigations, except for the total soundings, stopped at an embedded hard layer at approximately 30–35 m depth. On the other hand, the resistivity measurements did not detect this layer and showed continuous soil profiles to bedrock at greater depths in most of the area. The resistivity in the hard but thin layer was obviously not sufficiently different to show up in the interpretation. Regarding depth, the two models thus only coincide in the upper left corner, where the depth to bedrock was less and the upper bedrock surface was located above the elevation of the hard layer, which was not present here. Also at Utby, the leached and highly sensitive zones are mainly found in the upper part of the slope, where the thickness of the clay layers is less. However, in this case, the quick clay is found mainly in the upper parts of the profiles below the crust and the weathered zone. This reflects the

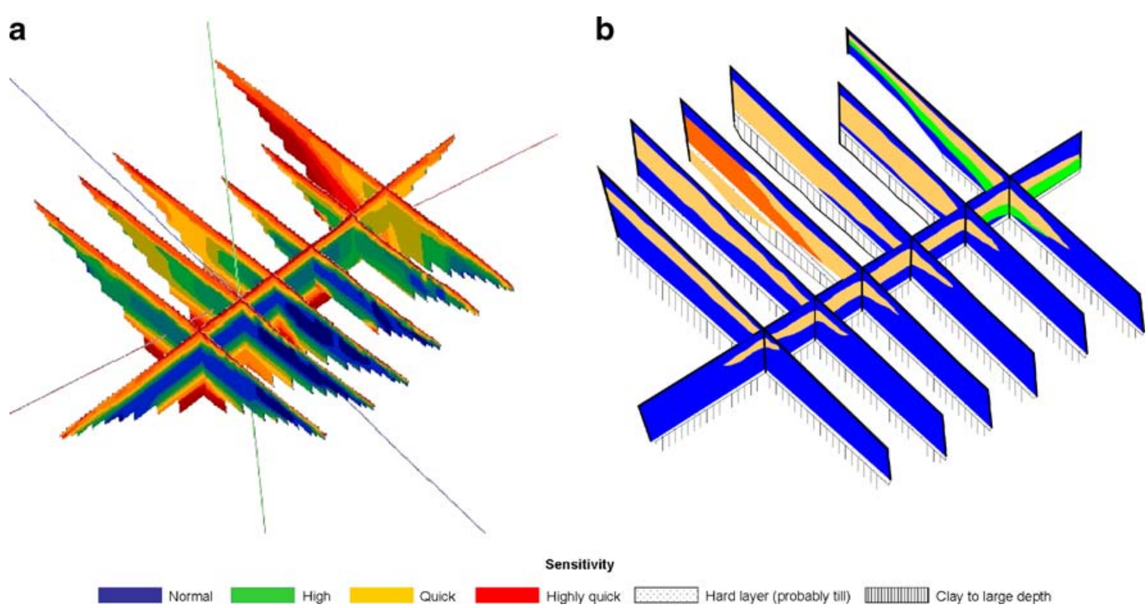


Fig. 22 Quasi 3-dimensional models of the soil at Utby. (**a**) Resistivity model, (**b**) Geotechnical model

groundwater conditions with a downward gradient and water slowly seeping down from the ground surface in these parts.

Conclusion

For the mapping of quick clay occurrence, it is possible to use any sounding method which uses a constant rate of advancement into the ground, and in which the penetration force applied on the top of the rods is measured. An almost vertical pushing force vs. depth curve generally indicates highly sensitive clay. There is an indirect correlation between change in total penetration force versus depth and sensitivity which depends on soil type, equipment, and test performance. The correlations can be used mainly for a rough division of the soil into sensitivity classes, and no precise rules can be given for the way in which this should be done.

Correlations between sensitivity and electrical resistivity can be used for separation of soil volumes in marine clays that have been leached sufficiently to possibly form quick clay from those volumes where the salt content remains high enough to prevent this. Results from this investigation confirmed the earlier rule (Söderblom 1969) that the resistivity should be ≥5 Ωm if the salt content is to be low enough to allow the clay to be quick. A higher electrical resistivity, however, does not always mean that the clay is quick. The actual sensitivity of the leached clay has to be determined by other methods, which can only provide sample tests. Other soil deposits that are rarely quick, such as soil in the dry crust and the weathered zone, as well as organic soils and heavily overconsolidated soils, should also be considered in the screening process.

The methods applied in the mapping of quick clay should be selected with consideration to cost and benefit, the suitability of the method in the particular geology and environment, and possible other uses of the results than quick clay mapping alone. The use of resistivity measurements is mainly applicable when large areas are to be investigated and in rural areas with a minimum of surface pavements and installations in the ground. Fills and thick overlying layers of unsaturated sand are also unfavorable for these measurements. A complex geology could also be a complication for this type of measurement and may require a 3D data acquisition and interpretation approach (Dahlin et al. 2007), but this is not normally the case in the Swedish areas of main interest. The results of resistivity measurements always have to be supplemented by geotechnical investigations, but these may be considerably limited in relation to those in a traditional geotechnical investigation even if the overall quality and reliability of the investigation is improved.

The simple static pressure sounding is normally sufficient for mapping quick clay. The use of the heavier rotary pressure sounding method did not show any particular advantage in the investigations in this project, except possibly that the method is somewhat faster. Rotary pressure sounding also better penetrates any coarse fills and layers overlying the clay. Both these methods can be replaced by the total sounding method, which yields corresponding results and also has the ability to penetrate stiffer layers and to verify the level of the bedrock. The CPT test with simultaneous measurement of the total penetration force gives the most reliable picture of the variation in sensitivity. However, the time and cost for this test is considerably higher and the interpretation more laborious. This may be more than compensated if the results are to be used for more than quick clay mapping, such as determination of the detailed stratigraphy, the undrained shear strength, and other parameters.

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Within the project, a report was presented by Rankka et al (2005). It contains three main parts (1) Processes leading to formation of quick clay; (2) Geological and hydrogeological conditions for formation of quick clay nature; (3) Mapping of quick clay formations by geotechnical and geophysical methods.

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References

Andersson-Sköld Y, Rankka K, Lind B, Odén K, Torrance K, Stevens R (2005) Quick clay—a case study of chemical perspective in Southwest Sweden. International Conference and Field Trip on Landslides. Tromsö

Auken E, Pellerin L, Christensen NB, Sørensen S (2006) A survey of current trends in near-surface electrical and electromagnetic methods. Geophysics 71(5):G249–G260

Bjerrum L (1954) Geotechnical properites of Norwegian clays. Geotechnique, Vol 4

Brenner RP, Nutalaya P, Chilingarian G, Robertson J (1981) Engineering geology of soft clay. In: Brand EW, Brenner RP (eds) Soft clay engineering. Elsevier

Dahlin T (2001) The development of electrical imaging techniques. Comput Geosciences 27(9):1019–1029

Dahlin T, Zhou B (2006) Gradient array measurements for multi-channel 2D resistivity imaging. Near Surface Geophysics 4:113–123

Dahlin T, Wisén R, Zhang D (2007) 3D effects on 2D resistivity imaging—modelling and field surveying results, Procs. Near Surface 2007—13th European Meeting of Environmental and Engineering Geophysics, 3–5 September 2007, Istanbul, Turkey, A15, 4 p

Hansbo S, Larsson R (1974) Stabilization and consolidation of clay by means of electroosmosis. Nordic Geotechnical Meeting. Copenhagen

Karlsson R, Hansbo S (1989) Soil classificiation and identification. Byggforskningsrådet Dokument D8:1989. Stockholm

Larsson R (1975) Konsolidering av lera med elektroosmos. Byggforskningsrådet. Rapport 45:1975. Stockholm. (in Swedish)

Larsson R, Åhnberg H (2003) Long-term effects of excavations at crests of slopes, pore pressure distribution—shear strength properties—stability–environment. Swedish Geotechnical Institute, Report No. 61, Linköping

Leroux V, Dahlin T (2003) Resistivity for mapping of quick clay—field study at Skepplanda, Utby and Munkedal in Bohuslän, Sweden. Report 2003-10-24. Department of Engineering Geology, Lund University, Lund

Loke MH, Acworth I, Dahlin T (2003) A comparison of smooth and blocky inversion methods in 2-D electrical imaging surveys. Explor Geophys 34(3):182–187

Løken T (1970) Recent research at the Norwegian Geotechnical Institute concerning the influence of chemical additions on quick clay. Geologiska föreningen i Stockhom. Förhandlingar. Volume 92, part 2. Stockholm

Lunne T, Robertson PK, Powell J (1997) CPT and piezocone testing in geotechnical practice. Blackie Academic and Professional, London

Magnusson N, Lundqvist G, Regnéll G (1963) Sveriges geologi. Nordstedts, Stockholm (In Swedish)

Moum J, Löken T, Torrance JK (1971) A geochemical investigation of the sensitivity of normally consolidated clay from Drammen, Norway, Geotechnique 21 (4)

Möller B, Bergdahl U (1982) Estimation of the sensitivity of soft clays from static and weight sounding tests. Proceedings of the European symposium on penetration testing, 2, ESOPT, Amsterdam, May 1982, Vol. 1

Norwegian Geotechnical Society (1982) Melding nr. 2. Oslo. (In Norwegian)

Penner E (1965) A study of sensitivity in Leda Clay. Can J Earth Sci 2:425–441

Pusch R (1970) Clay microstructure. A study of the microstructure of soft clays with special reference to their physical properties. Swedish Geotechnical Institute, Proceedings No 24. Stockholm

Rankka K, Andersson-Sköld Y, Hultén C, Larsson R, Leroux V, Dahlin T (2005) Quick clay in Sweden. Report 65. Swedish Geotechnical Institute, Linköping

Robitaille D, Demers D, Potvin J, Pellerin F (2002) Mapping of landslide-prone areas in the Saguenay region, Quèbec, Canada. Instability—planning and management. Tomas Tellford, London

Rosenqvist IT (1946) Om leirers kvikkagtighet. Statens Vegvesen. Veglaboratoriet. Meddelande Nr 4. Oslo. (In Norwegian)

Rygg N (1978) Dreietrykksondering: Tolkning av sonderingsresultat. Vegdirektoratet, Veglaboratoriet, Intern rapport nr. 816, Oslo. (In Norwegian)

SGF (1996) Geoteknisk fälthandbok. Allmänna råd och metodbeskrivningar. Svenska Geotekniska Föreningen. SGF Rapport 1:96, Linköping, (In Swedish)

Solberg I (2007) Geological, geomorphological and geophysical investigations of areas prone to clay slides: examples from Buvika, Mid Norway. Doctoral thesis. Norwegian University of Science and Technology, Faculty of Engineering Science and Technology, Department of Geology and Mineral Resources Engineering. Trondheim

Statens vegvesen (1997) Feltundersøkelser—retningslinjer, Håndbok 015. Vegdirektoratet, Veglaboratoriet, Oslo (In Norwegian)

Swedish Standard 02 71 25E (1991) Geotechnical tests—undrained shear strength—fall-cone test

Söderblom R (1969) Salt in Swedish clays and its importance for quick clay formation. Results form some filed and laboratory studies. Swedish Geotechnical Institute, Proceedings No 22. Stockholm

Söderblom R (1974) Organic matter in Swedish clays and its importance for quick clay formation. Swedish geotechnical Institute, Proceedings No 26. Stockholm

Talme O, Pajuste M, Wenner C-G (1966) Secondary changes in the strength of clay layers and the origin of sensitive clay. Byggforskningsrådet, Rapport 56. Stockholm. (In Swedish)

Torrance JK (1974) A laboratory investigation of the effect of leaching on the compressibility and shear strength of Norwegian marine clays. Geotechnique 24(No 2):155–173

Torrance JK (1978) Post-depositional changes in the pore-water chemistry of the sensitive marine clays of the Ottawa area, eastern Canada. Eng Geol 14:135–147

Viberg L (1984) Landslide risk mapping in soft clays in Scandinavia and Canada. 4th International symposium on landslides. Volume 1. Toronto

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