Relationship between electrical resistivity and basic geotechnical parameters for marine clays


Published in:
Canadian Geotechnical Journal

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
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Abstract: Recently, considerable efforts have been made in the attempt to map quick clay areas using electrical resistivity measurements. However there is a lack of understanding regarding which soil parameters control the measured resistivity values. To address this issue, inverted resistivity values from 15 marine clay sites in Norway have been compared with basic geotechnical index properties. It was found that the resistivity value is strongly controlled by the salt content of the pore fluid. Resistivity decreases rapidly with increasing salt content. There is also a relatively clear trend of decreasing resistivity with increasing clay content and plasticity index. Resistivity values become very low (≈5 Ω·m) for high clay content (>50%), medium- to high-plasticity (I_p ≥ 20%) materials with salt content values greater than about 8 g/L (or corresponding remoulded shear strength values greater than 4 kPa). For the range of values studied, there is poor correlation between resistivity and bulk density and between resistivity and water content. The data studied suggest that the range of resistivity values corresponding to quick clay is 10 to 100 Ω·m, which is consistent with other published limits. A comparison is made between two-dimensional electrical resistivity tomography (ERT) and resistivity cone penetration test (RCPTU) data for two of the sites and the two sets of data show similar trends and values irrespective of scale effect.

Key words: marine clay, quick clay, geophysics, resistivity, laboratory testing, Norway.

Résumé : Récemment, des efforts considérables ont été déployés dans le but de cartographier les zones d’argile sensible à l’aide de mesures de résistivité électrique. Cependant, on ne comprend pas encore bien quels paramètres des sols contrôlent les mesures de résistivité obtenues. Pour remédier à cette situation, des valeurs de résistivité obtenues sur 15 sites d’argile marine en Norvège ont été comparées aux propriétés géotechniques de base. Il a été déterminé que la valeur de la résistivité est fortement contrôlée par le contenu en sel du fluide interstitiel. La résistivité diminue rapidement lorsque le contenu en sel augmente. On observe aussi une tendance claire à la diminution de la résistivité lorsque le contenu en argile et l’indice de plasticité augmentent. Les valeurs de résistivité deviennent très faibles (≈ 5 Ω·m) pour des teneurs en argile élevées (>50%), pour des matériaux ayant une plasticité moyenne à élevée (I_p ≈ 20%) avec des valeurs de contenu en sel supérieures à environ 8 g/L (ou des valeurs de résistance au cisaillement remoulée correspondantes supérieures à 4 kPa). Pour la gamme de valeurs étudiées, la corrélation entre la résistivité et la masse volumique apparente, et entre la résistivité et la teneur en eau, est faible. Les données étudiées suggèrent que la gamme de valeurs de résistivités correspondant à l’argile sensible est de 10 à 100 Ω·m, ce qui concorde avec d’autres limites publiées. Une comparaison est présentée entre les données de tomographie en résistivité électrique (ERT) à deux dimensions et l’essai de résistivité de pénétration au cône (RCPTU) pour deux sites, et les deux séries de données démontrent des tendances similaires et des valeurs ne tenant pas compte de l’effet d’échelle.

Mots-clés : argile marine, argile sensible, géophysique, résistivité, essais en laboratoire, Norvège.

[Traduit par la Rédaction]
Introduction

In recent years considerable efforts have been made in Norway and Sweden with respect to mapping of quick clay formations using combined geotechnical and geophysical methods. Although it was recognised that some intrusive geotechnical investigations will always be necessary, the objective of these studies was to develop techniques to maximize the use of noninvasive relatively simple geophysical surveys such as electrical resistivity tomography (ERT). For example, Solberg et al. (2008a, 2012) and Lecomte et al. (2008b) describe the use of resistivity measurements for mapping quick clay at landslide areas at Buvika, mid Norway; Rødde, mid Norway; and Finneidfjord, northern Norway; respectively. Donohue et al. (2011) and Pfaffhuber et al. (2010) detail integrated geophysical work with similar objectives for a site at Smøgrav in Southern Norway and Sauvin et al. (2011) outline comparable work at an adjacent site at Vålen. Similar work in Sweden has been published by Dahlin et al. (2005), Lundström et al. (2009), and Löfroth et al. (2011).

Parallel work has been carried out on use of the resistivity cone penetration test (RCPTU) in quick clay areas in both Norway (e.g., Rømøen et al. 2010) and in Sweden (Dahlin et al. 2004; Schällin and Tornborg 2009; Löfroth et al. 2011).

Although most recent research efforts on this topic have taken place in Scandinavia, quick clays continue to pose a hazard in other countries such as Canada (Geertsema and Torrance 2005) and Japan (Torrance and Ohtsubo 1995).

Perhaps not surprisingly these studies found that there is no simple correlation between resistivity and sensitivity, as they can be influenced by factors such as the density, water content, silt fraction, fabric and structures of the soil, chemistry of the pore fluid, and mineralogy of the clay particles.

The objective of the present work is to investigate the influence of the basic index parameters of Norwegian clays on the measured resistivity values to obtain a deeper understanding of what controls the values. The ultimate intention is to provide assistance to practicing engineers in the interpretation of resistivity surveys in marine clay areas.

In this study, clay properties from geotechnical testing are compared with resistivity data, mainly from ERT, at 15 sites. At three of the sites (Rissa, Finneidfjord, and Kattmarka), large destructive quick clay landslides had occurred; see Gregersen (1981) and L’Heureux et al. (2011a), Longva et al. (2003) and L’Heureux et al. (2011b), and Nordal et al. (2009) and Solberg et al. (2011), respectively.

The sites

The location of the sites is shown in Fig. 1. The sites are all located in coastal areas of Norway coinciding with those locations underlain by elevated marine clays. The sites may be grouped as follows:

- Mid Norway: Berg, Rissa, Rødde, and Buvika.
- North Trøndelag and Northern Norway: Finneidfjord and Kattmarka.

A summary of the soil properties at the 15 sites surveyed is given in Table 1. The clay is characterized by water content (\(w\)) of 20% to 50%, unit weight (\(\gamma\)) of 17 to 20.5 kN/m\(^3\), relatively high clay content (10% to 50%), low medium plasticity (\(I_p\) in range 2% to 30%), and of soft to firm consistency (undrained shear strength, \(s_u\), in the range 10 to 40 kPa). Sensitivity (\(S_s\)) is the most variable parameter, varying from 2 to extremely high values of the order of 350. The exception is the Farriseidet site, which is underlain by organic clay of low unit weight and high water content.

Electrical resistivity tomography (ERT)

Background

The use of two-dimensional (2D) resistivity measurements as a tool for subsurface profiling has expanded during the last 10 years due to advances in the measurement technique and the data acquisition and processing software. The development has also been driven by the relatively high cost of traditional drilling and sampling techniques. Two-dimensional resistivity measurements give a continuous and, ideally when combined with other geophysical methods such as reflection seismic and ground penetrating radar, relatively detailed picture of the subsurface within a short time. In an area without previous investigations, the 2D resistivity method gives an overview of the subsurface as a basis for further investigation and for the determination of optimal locations for drilling. The method is a cost effective and valuable complement to drilling as it can separate intact marine clay deposits (high salt content – low resistivity) from quick clay (low salt content – higher resistivity), in addition to identifying coarser material and bedrock. Typical resistivity values for various materials are summarized in Table 2, which is modified from Solberg et al. (2012).

Equipment and data acquisition

The ERT surveys at eight of the nine southern Norway sites were carried out by APEX Geoservices – UCD. The ex-
<table>
<thead>
<tr>
<th>Location</th>
<th>Soil type</th>
<th>Depth (m)</th>
<th>w (%)</th>
<th>$\gamma$ (kN/m³)</th>
<th>Clay (%)</th>
<th>$I_p$ (%)</th>
<th>$s_u$ (kPa)</th>
<th>$S_t$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Southern Norway</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skøyen – Asker</td>
<td>0–2 m dry crust, 2–5 m low sensitive clay, 5–16.5 m (proven) quick clay</td>
<td>2–5</td>
<td>30–40</td>
<td>17.6–18.4</td>
<td>n/a</td>
<td>6 one value only</td>
<td>10–40</td>
<td>2–12</td>
<td>Norwegian Geotechnical Institute (NGI files)</td>
</tr>
<tr>
<td>RVII - Hilleren</td>
<td>0–4 m dry crust, 4–15 m, low sensitive clay, 12–35 m medium sensitive clay</td>
<td>5–16.5</td>
<td>20–35</td>
<td>18.1–20.6</td>
<td>—</td>
<td>—</td>
<td>10–15</td>
<td></td>
<td>NGI files</td>
</tr>
<tr>
<td>Drammen - Museumpark</td>
<td>0–4 m fine sand, 4–12 m low sensitive plastic clay, 12–35 m lean clay</td>
<td>15–</td>
<td>33–38</td>
<td>17.5–19.5</td>
<td>40–45</td>
<td>5–13</td>
<td>5–25</td>
<td>5–30</td>
<td>Long et al. (2009)</td>
</tr>
<tr>
<td>Ferriseidet</td>
<td>0–3m peat, 3–8 m quick clay, rock at 8m</td>
<td>0–3</td>
<td>&gt;400</td>
<td>10.5</td>
<td>n/a</td>
<td>n/a</td>
<td>8</td>
<td>10</td>
<td>Bjerrum(1967), Lunne and Lacasse(1999)</td>
</tr>
<tr>
<td>Skienselven</td>
<td>0–6 m silty sandy clay, 6–10.7 m (proven) quick clay</td>
<td>3–8</td>
<td>75–120</td>
<td>13.8–15.4</td>
<td>29–49</td>
<td>13–27</td>
<td>7–28</td>
<td>70–140</td>
<td>NGI files</td>
</tr>
<tr>
<td>Månejordet</td>
<td>0–2 m dry crust, 2–5.5 m low sensitive sandy clay, 5.5–14.5 m quick clay</td>
<td>2.5–5.5</td>
<td>28–50</td>
<td>18–20.5</td>
<td>20</td>
<td>14–26</td>
<td>30–45</td>
<td>&lt;10</td>
<td>Statensvegvesen / UCD files</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.5–14.5</td>
<td>25–40</td>
<td>18–19.5</td>
<td>24–27</td>
<td>6–9</td>
<td>20–50</td>
<td>50–350</td>
<td>Statensvegvesen / UCD files</td>
</tr>
<tr>
<td>Smørggrav</td>
<td>0–5 m soft clay</td>
<td>0–5</td>
<td>27–42</td>
<td>17.9–18.5</td>
<td>41–57</td>
<td>13–14</td>
<td>37</td>
<td>19</td>
<td>Donohue et al. (2011), Pfaffhuber et al. (2010)</td>
</tr>
<tr>
<td><strong>Mid Norway</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 1. Summary of soil types and material properties for sites surveyed.
cept is Vålen where the work was done by the Norwegian Geotechnical Institute (NGI). The work at the six sites in mid Norway and northern Norway was performed by the Geological Survey of Norway (NGU).

Similar techniques were used at all sites. For the APEX–UCD surveys, data was acquired using a multi-electrode Campus Tigre resistivity meter with a 32-takeout multi-core cable and 32 conventional stainless steel electrodes. An electrode spacing of 3 m was used as the default. However at several of the sites a 5 m spacing was also used to provide deeper data (e.g., at E16 Kjørby – Wøyen and RVII–Hille- ren). As the subsurface layers were not expected to deviate significantly from the horizontal, a four-electrode Wenner array configuration was used to acquire multiple readings for each ERT profile. The Wenner array also generally provides a good signal to noise ratio (Donohue et al. 2011).

The work at Vålen employed a Terrameter LS with four cables of 21 takeouts (81 active electrodes). A roll-along gradient configuration with 2 and 4 m electrode spacing was used to acquire the data, leading to a total profile length of 160 to 320 m.

The equipment used by NGU was the Lund system, developed by Dahlin (1993), comprising a relay box (ABEM ES10–64) and four multi-electrode cables and 81 active stainless steel electrodes, controlled by an ABEM Terrameter SAS 4000. The distance between the electrodes was generally 5 m and occasionally 2 or 10 m. Both the Wenner and Gradient array systems were used. The Gradient array can yield up to seven times more data than the Wenner array in a shorter time and thus can be useful for examining lateral changes in resistivity (Dahlin and Zhou 2006).

**Data processing**

In all cases the data processing and inversion was carried out using the software Res2Dinv (Loke 2007). This software uses a forward-modelling subroutine to calculate the apparent resistivity values and a nonlinear least-squares optimization technique (Loke and Barker 1996). In a study of synthetic data to represent marine clays, Reiser et al. (2010) showed that “smooth” inversion with a vertical–horizontal filter of 0.5 resulted in the most accurate inversion models.

The least-squares equations resulting from the inversion process were solved using the Gauss–Newton method. As there occasionally was a large subsurface resistivity contrast, the Gauss–Newton method was used for the first two to three iterations, then the quasi-Newton method was employed. The latter allows an approximate solution within a predefined convergence limit. This was found to provide the best compromise between computational time and accuracy (Loke and Dahlin 2002). Most inversions performed converged to root mean square (RMS) errors of less than 6% within five to six iterations and the final RMS errors were usually less than 1.5%.

**Soil sampling and testing**

In Norway, the standard site investigation procedure is to recover continuous piston samples of unconsolidated overbur-
Table 2. Typical resistivity values for various materials (modified from Solberg et al. 2012).

<table>
<thead>
<tr>
<th>Resistivity (Ω·m)</th>
<th>Main characterization</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–10</td>
<td>Unleached marine clay deposits</td>
<td>The clay has been exposed to little leaching since deposition. The pores in the clay still contain salt water, which stabilize the structure. Because of the large concentration of ions in the pore water, the conductivity of the clay is good, and thus the resistivity values are low.</td>
</tr>
<tr>
<td>10–100</td>
<td>Leached clay deposits</td>
<td>Sensitive clay develops as groundwater leaches ions from the marine clay. The electrical conductivity of the deposit is still high, but not as good as for the unleached marine clay. Other sediment features can give resistivity values similar to those of quick clay: further leached marine clay (not quick anymore), silt, and fine-grained till.</td>
</tr>
<tr>
<td>&gt;100</td>
<td>Dry crust clay deposits, coarse sediments, (bedrock)</td>
<td>Dry crust clay; remoulded, dry clay from quick-clay landslides; and coarser materials like sand and gravel will have higher resistivity values than marine clay. Most bedrock types will have values of several thousand Ω·m.</td>
</tr>
</tbody>
</table>

Results and correlations

Inverted resistivity values were extracted from the R-se2Dinv data files. A one-dimensional (1D) plot of resistivity versus depth at the location of the relevant borehole was made and the results compared with the geotechnical parameters obtained from piston samples extracted from the same depth. In each case a resistivity profile and a matching borehole, i.e., a borehole on the same line as the resistivity section or located at most 5 m from the section, was used.

Resistivity and salt content of pore fluid

The relationship between resistivity and salt content of the pore fluid is shown in Fig. 2. Unfortunately as salt content is not measured routinely in all investigations, the amount of data is relatively limited. As expected the link between these two parameters is strong. Resistivity decreases rapidly with increasing salt content and reaches a low value of about 5 Ω·m and becomes more or less constant once the salt content exceeds approximately 8 g/L. The exponential trendline shows a relatively good coefficient of correlation, $R^2$, value of 0.8.

In the past authors such as Bjerrum (1954) and Rosenqvist (1955) have suggested that clay becomes quick (i.e., sensitivity $S_t > 30$ and remoulded shear strength $s_u < 0.5$ kPa) when the salt content is less than 5 g/L. Subsequently Torrance (1974) suggested the limit should be 2 g/L. The plot of sensitivity versus salinity of the pore fluid, shown in Fig. 3, shows that although all of the quick clay data points have a salt content less than 5 g/L, there are also a significant number of data points with a salt content less than 2 or 5 g/L for which the sensitivity is less than 30. In addition, Andersson-Sköld et al. (2005) measured a salinity of 5.6 g/L in Swedish quick clay. Nonquick marine clay may also contain very low salt content due to continued leaching or weathering.

This illustrates that although salt content of the pore fluid...
is a very important controlling factor, sensitivity of marine clay is also influenced by other factors (Mitchell 1993).

**Resistivity and clay content**

The relationship between resistivity and clay content is shown in Fig. 4. There is a relatively strong correlation between the two properties, with resistivity decreasing with increasing clay content. This finding is as expected as clay particles facilitate surface conductance of electrical current. Those sites with relatively low clay content (e.g., the comparatively silty materials at Finneidfjord, Kattmarka, and Rødde) show high resistivity values. Beyond clay content of about 40% (by mass) the resistivity values are generally low. The polynomial trendline shown has a reasonable $R^2$ value of 0.59.

**Resistivity and plasticity index**

A similar pattern, to that of clay content, emerges in the plot of resistivity against plasticity index ($I_p$) in Fig. 5. Note there are unfortunately relatively few data points for high-plasticity clays with $I_p > 20\%$. Again there is a reasonably strong trend of reducing resistivity due to increasing $I_p$. This is consistent for the finding for clay content above, as $I_p$ will increase with increasing clay content. However $I_p$ in sensitive clays varies not only with the grain size of the soil, but also
with the intensity of the leaching. For example, Bjerrum (1954) showed that leaching by fresh water of a Norwegian marine clay resulted in a drop in the liquid limit from 45% to 25%, while the plastic limit shows a much lower reduction from about 20% to 17%. Hence the sensitive clays may show a relatively lower $I_p$ than a similar nonsensitive clay, thus making any correlation between resistivity and $I_p$ more complex.

Nonetheless for the data presented here beyond an $I_p$ value of about 20%, corresponding to the upper limit of medium plasticity (Norsk Geoteknisk Forening (NGF 1982)), the resistivity values are low ($\approx 5 \text{ \Omega \cdot m}$) and more or less constant. For the low-plasticity materials the resistivity values are generally higher, but are more scattered, probably due to the reasons discussed above. Some attempts were made to fit a trendline through the data, but the resulting $R^2$ value was poor.

**Resistance and remoulded shear strength**

As remoulded shear strength ($s_{ur}$) is directly related to the salt content of the pore fluid, one would expect a strong link between resistivity and $s_{ur}$ (as measured by the fall cone). In addition, leaching decreases the liquid limit of marine clays and consequently the remoulded shear strength (Mitchell and Soga 2005). As seen in Fig. 6, resistivity decreases rapidly with increasing remoulded shear strength and becomes more or less constant when the $s_{ur}$ value exceeds 4 kPa. The rea-
sons for the relatively high values at the RVII – Hilleren site are unclear and warrant further study. Remoulded shear strength values in silty materials needs to be treated with caution as the shearing action may not be totally undrained, leading to possible relatively high values.

In Fig. 7, the focus is on those values where \( s_{ur} \) is less than 0.5 kPa, which is the threshold for quick clay according to NGF (1982). There is a clear trend of increasing resistivity with decreasing \( s_{ur} \). This is consistent with the fact that \( s_{ur} \) will decrease with increasing intensity of leaching. Solberg et al. (2012) reviewed a large body of data and found that 10 to 100 \( \Omega \cdot m \) represented the resistivity range for quick clay. Although most of the data discussed here is within this range, some of the sites with relatively high silt content (e.g., Skienselven, Rødde, and Kattmarka) exhibit significantly higher resistivity values up to 150 \( \Omega \cdot m \).

Resistivity and sensitivity

Sensitivity is the ratio of peak \( (s_u) \) to remoulded shear strength \( (s_{ur}) \). Unfortunately the values of \( s_u \) and \( s_{ur} \) are not unique and will vary with the test type, mode of deformation, stress conditions, and strain rate, amongst other factors. In turn, the absolute value of sensitivity will depend on the test used. For consistency, in this study the results from only the Swedish fall cone tests have been used. This test is the one most widely used in Scandinavia. Leaching will have a much stronger effect on \( s_{ur} \) than \( s_u \). In fact, the \( s_u \) value will be largely unaffected. Thus a good relationship between resistivity and sensitivity is to be expected.

Resistivity values are plotted against sensitivity (from the fall cone) in Fig. 8. There is a good relationship between the two properties, with resistivity increasing more or less linearly with sensitivity. The increase in scatter of the data with increasing \( s_u \) is due to the decreasing accuracy of the fall cone measurements.

The high values for Skienselven, Rødde, and Kattmarka are due to the silty nature of the material as presented above. The relatively high values for RVII need to be investigated further.

Resistivity and bulk unit weight

The relationship between resistivity and bulk unit weight is shown in Fig. 9. Intuitively one would expect resistivity to decrease with increasing unit weight (or density) as the particles are forced closer together. For the bulk of the data, where the resistivity is less than 50 \( \Omega \cdot m \), there is some weak tendency for decreasing resistivity with increasing bulk unit weight. However the trends are far from clear and vary from site to site. For example, the Rissa data follows the expected trend whereas the Smørgårv data shows the opposite tendency. Some sites, for example Skøyen – Asker, show relatively constant resistivity for a range of unit weight values.

The higher resistivity values recorded for the sites at Skienselven, Finneidfjord, and Kattmarka fall outside the general trend and can be attributed to the silty nature of these materials. The Farrisiedet site shows low bulk unit weight values due to the organic nature of the material.

It would seem that, although bulk unit weight plays a role in the resulting measured resistivity, its influence is outweighed by other factors.

Resistivity and water content

Inverted resistivity values are plotted against water content in Fig. 10. There is no clear pattern in the plot, even for the main body of the data where the resistivity is less than 50 \( \Omega \cdot m \). Similar to the relationship with bulk unit weight, the values for the materials with either high silt or –sand content or high organic content fall well away from the main body of the data.

Discussion

Resistivity and geotechnical properties

The data presented above shows that the measured resistivity values depend on a number of interrelated factors. It is difficult to separate the influence of each individual parameter. In Fig. 8, for example, an attempt has been made to do this, where the clay content values have been superimposed on the plot of resistivity against sensitivity. Although the higher clay content materials correspond to the lower resistivity values, there is insufficient data or insufficient trends to plot, e.g., contours of clay content on the diagram.

The data shows that resistivity is strongly influenced by the salt content of the pore fluid and also influenced significantly by the clay content and plasticity of the material. It could be argued that the data for clay content and plasticity index in Figs. 4 and 5 merely reflect reducing salt content. However these figures contain more data than shown in Fig. 6 and include data for sites where the remoulded shear strength (and hence salinity) are similar.

For the data available, no relationship was found between resistivity and water content. However as the range of values studied here is relatively limited, and many other studies have shown the importance of water content on measured resistivity, this finding will not be universally applicable.

ERT versus RCPTU

The data presented in this study compares point data (laboratory measurements) with larger soil volumes (geophysical data) and scale effects may therefore arise. The influence of such scale effects may be studied by comparing ERT data with the previously mentioned resistivity cone penetration test (RCPTU). The latter involves an 80 cm long, 4.4 cm diameter module on which four ring electrodes are mounted. The two outer rings apply current and the two inner rings measure the voltage. The distance between the two outer rings is approximately 20 cm, and thus the RCPTU measurements relate to a small, relatively homogenous, body of soil similar in scale to a soil sample. Unlike ERT data, RCPTU results do not need to be inverted. Pfaffhuber et al. (2010) illustrate how RCPTU data can be used successfully to constrain an ERT inversion process.

There is some evidence that RCPTUs will give slightly lower resistivity values in the high sensitive clay zones. Schälin and Tornborg (2009) found RCPTU measurements in highly sensitive clay could be 2 to 3 \( \Omega \cdot m \) lower than ERT inverted data. This is also in agreement with the work of Fukue et al. (1999) who showed that remoulded clay has better conductivity than undisturbed clay, as the breakage of the chemical bonding between the clay particles will decrease the resistivity. Sauvin et al. (2011) found good agreement between ERT and RCPTU data for the Vålen research site.

PROOF/ÉPREUVE
Dahlin et al. (2004) also found good correlation between ERT and RCPTU data, but their study did not include quick clays.

Figure 11 shows a comparison of ERT and RCPTU data from tests sites at Rissa (Figs. 11a and 11b) and Rødde (Fig. 11c). The data are taken from Solberg et al. (2010) and Solberg et al. (2012), respectively. The two sets of data for Rissa show that the RCPTU data can give either lower or higher resistivity values than for the ERT data. Overall, the relationship between the two sets of data at both sites is very good and confirms the reliability and applicability of the ERT data for the present purposes.

Possible methodical weaknesses with ERT
Two-dimensional ERT data measured at the surface may suffer from some methodical weaknesses. Effects of three-dimensional geology may influence the measured resistivity values and consequently the inverted 2D resistivity section. In addition, the principles of equivalence and suppression may influence the inverted sections (Reynolds 2011). Suppression appears when resistivity in one layer lies between the resistivity of the surrounding layers while equivalence appears on ascending or descending resistivity towards the depth. Anisotropic resistivity may also influence the results when data from different methods are compared. The effects of these weaknesses are nonunique inversion results.

Nonetheless, the comparison between ERT and RCPTU data, shown in Fig. 11, confirms there is a good correlation between 2D surface and 1D borehole resistivity data. However, in detail there are deviations that make it necessary to have great and partly overlapping intervals for the resistivity in different materials in an interpretational model. The present study will give a better understanding of what kind of geotechnical information can be extracted from the resistivity data.

Conclusions and recommendations
The ultimate objective of this work was to provide assistance for practicing engineers in the interpretation of resistivity surveys in glacio-marine and marine clay areas by studying the influence of basic geotechnical parameters on resistivity values from 2D measurements. It was found that

1. There is a strong link between resistivity and both salt content of the pore fluid and remoulded shear strength. Resistivity decreases rapidly with increasing salt content or remoulded shear strength. The resistivity values become more or less constant if the salt content is greater than about 8 g/L and the remoulded shear strength is greater than 4 kPa.

2. There is a trend of decreasing resistivity with increasing clay content and plasticity index. Although these trends are not conclusive, for high-plasticity clays, with $I_p \approx 20\%$ and clay content >50%, the measured resistivity values are very low ($\approx 5 \, \Omega \cdot m$).

3. It would seem that, although bulk density plays a role in the resulting measured resistivity, its influence is outweighed by other factors such as salt content of the pore fluid and clay content.

4. The data presented here suggest that the range of resistivity values corresponding to quick clay is 10 to 100 $\Omega \cdot m$, and this is consistent with other published limits. Thus ERT surveys alone are not sufficient for mapping quick clay and need to be supplemented with conventional drilling and sampling.

5. A comparison of ERT and RCPTU data show comparable trends and similar resistivity values. This confirms that the ERT data, which represent bulk resistivity, can give sufficiently accurate information on local soil conditions. For future work it would be useful to
• Extend the range of clays studied to those of higher plasticity.
• Carry out additional work on silt sites to examine the controlling factors on resistivity for these materials.

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