

## Relationship between electrical resistivity and basic geotechnical parameters for marine clays

Long, M., Donohue, S., L'Heureux, J-S., Solberg, I-L., Rønning, J. S., Limacher, R., ... Lecomte, I. (2012). Relationship between electrical resistivity and basic geotechnical parameters for marine clays. *Canadian Geotechnical Journal*, 49(10), 1158-1168. DOI: 10.1139/T2012-080

**Published in:**  
Canadian Geotechnical Journal

**Document Version:**  
Peer reviewed version

**Queen's University Belfast - Research Portal:**  
[Link to publication record in Queen's University Belfast Research Portal](#)

### General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

### Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact [openaccess@qub.ac.uk](mailto:openaccess@qub.ac.uk).



# Relationship between electrical resistivity and basic geotechnical parameters for marine clays

**Michael Long, Shane Donohue, Jean-Sebastien L'Heureux, Inger-Lise Solberg, Jan Steinar Rønning, Romaric Limacher, Peter O'Connor, Guillaume Sauvin, Magnus Rømoen, and Isabelle Lecomte**

**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 ( $\approx 5 \Omega\cdot\text{m}$ ) for high clay content (>50%), medium- to high-plasticity ( $I_p \approx 20\%$ ) 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  $\Omega\cdot\text{m}$ , 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 ( $\approx 5 \Omega\cdot\text{m}$ ) pour des teneurs en argile élevées (>50%), pour des matériaux ayant une plasticité moyenne à élevée ( $I_p \approx 20\%$ ) 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  $\Omega\cdot\text{m}$ , 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]

Received 2 February 2012. Accepted 2 August 2012. Published at [www.nrcresearchpress.com/cgi](http://www.nrcresearchpress.com/cgi) on .

**M. Long and R. Limacher.** Department of Civil, Structural and Environmental Engineering, University College Dublin (UCD), Newstead Building, Belfield, Dublin 4, Ireland.

**S. Donohue.** University of Bath, Bath, UK; formerly University College Dublin (UCD), Dublin, Ireland.

**J.-S. L'Heureux.** Geological Survey of Norway (NGU), Trondheim, Norway; International Centre for Geohazards (ICG) at NGI, Oslo, Norway.

**I.-L. Solberg.** Geological Survey of Norway (NGU), Trondheim, Norway.

**J.S. Rønning.** Geological Survey of Norway (NGU), Trondheim, Norway; Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

**P. O'Connor.** APEX Geoservices, Gorey, Co. Wexford, Ireland.

**G. Sauvin.** International Centre for Geohazards (ICG) at NGI, Oslo, Norway; NORSAR, Kjeller, Norway; University of Oslo (UiO), Oslo, Norway.

**M. Rømoen.** Norwegian Geotechnical Institute (NGI), Oslo, Norway.

**I. Lecomte.** International Centre for Geohazards (ICG) at NGI, Oslo, Norway; NORSAR, Kjeller, Norway.

**Corresponding author:** Mike Long (e-mail: [Mike.Long@ucd.ie](mailto:Mike.Long@ucd.ie)).

## 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 nonintrusive relatively simple geophysical surveys such as electrical resistivity tomography (ERT). For example Solberg et al. (2008, 2012) and Lecomte et al. (2008a) 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 Smørgrav 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., Rømoe et al. 2010) and in Sweden (Dahlin et al. 2004; Schälén 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.

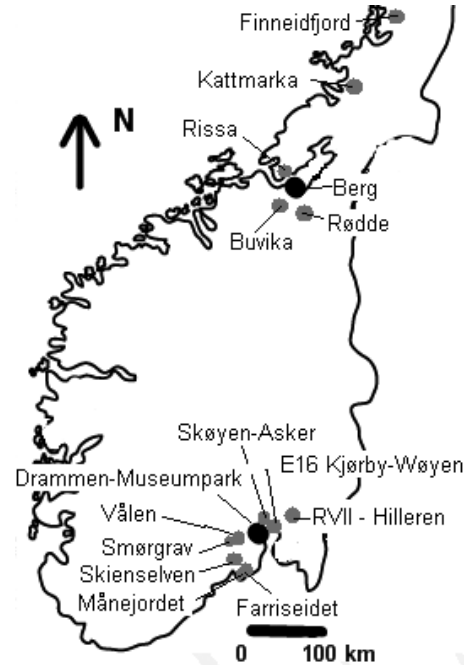
## The sites

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:

- Southern Norway: E16Kjørby – Wøyen, Skøyen – Asker, RVII – Hilleren, Drammen – Museumpark, Farriseidet, Skienselven, Månejordet, Smørgrav, and Vålen.
- 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 con-

Fig. 1. Site locations.



tent ( $w$ ) of 20% to 50%, unit weight ( $\gamma$ ) of 17 to 20.5 kN/m<sup>3</sup>, relatively high clay content (10% to 50%), low to 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 ( $S_t$ ) 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 1.** Summary of soil types and material properties for sites surveyed.

Location	Soil type	Depth (m)	w (%)	$\gamma$ (kN/m <sup>3</sup> )	Clay (%)	$I_p$ (%)	$s_u$ (kPa)	$S_t$	References
<b>Southern Norway</b>									
E16 Kjørby – WøyenBH1054	0–2 m dry crust, 2–15 m medium sensitive clay (organic?), 15–35 m quick clay	2–15	20–55	16.5–19	6–21	9–18	35–45	8–23	Rømoe et al. (2010)
E16 Kjørby – WøyenBH1306	Soft clay medium sensitive	15–35 1.5–10.2	30–40 32–51	17.5–19 16.6–19	46 n/a	6–9 9–17	20–55 18–33	>30 5–26	Rømoe et al. (2010) Rømoe et al. (2010)
Skøyen – Asker	0–2 m dry crust, 2–5 m low sensitive clay, 5–16.5m (proven) quick clay	2–5	30–40	17.6–18.4	n/a	6 one value only	10–40	2–12	Norwegian Geotechnical Institute (NGI) files
RVII - Hilleren	0–4 m dry crust, 4–15 m, low sensitive clay, 15–26 m (proven) medium sensitive clay	5–16.5 4–15	20–35 31–42	18.1–20.6 18–19	— 30–44	— 11–21	10–15 10–35	3–9>80	NGI files Long et al. (2009)
Drammen -Museumpark	0–4 m fine sand, 4–12 m low sensitive plastic clay, 12–35 m lean clay	15– 4–12	33–38 40–55	17.5–19.5 16.5–17	40–45 40–42	5–13 20–30	5–25 25–30	5–30 6–10	Long et al. (2009) Bjerrum(1967), Lunne and Lacasse(1999)
Farriseidet	0–3m peat, 3–8 m quick (organic?) clay, rock at 8m	12–20 0–3	30 >400	18.5–19.5 10.5	32–39 n/a	10 n/a	33–33 8	3–5 10	Bjerrum(1967), Lunne and Lacasse(1999) NGI files
SkienSelven	0–6 m silty sandy clay, 6–10.7 m (proven) quick clay	3–8 6–10.7	75–120 26–33	13.8–15.4 19.1–19.7	29–49 n/a	13–27 3	7–28 10–24	70–140 110–240	NGI files NGI files
Månejordet	0–2 m dry crust, 2–5.5 m low sensitive sandy clay, 5.5–14.5 m quick clay	2.5–5.5 5.5–14.5	28–50 25–40	18–20.5 18–19.5	20 24–27	14–26 6–9	30–45 20–50	<10 50–350	Statensvegvesen / UCD files Statensvegvesen / UCD files
Smørgrav	0–5 m soft clay	0–5	27–42	17.9–18.5	41–57	13–14	37	19	Donohue et al. (2011), Pfaffhuber et al. (2010)
	5–13 m quick clay	5–13	38–45	17.8–18.3	37–44	10–15	19–25	23–63	Donohue et al. (2011), Pfaffhuber et al. (2010)
	13–22 m soft clay	13–22	39–46	17.8–18.2	53–58	20–22	24–28	5–6	Donohue et al. (2011), Pfaffhuber et al. (2010)
Vålen	Soft to firm low sensitive clay	3.2–22.2	37–47	18.2–19.6	36.6–39.4	16.4–20.3	12–34	2–15	Sauvin et al. (2011)
<b>Mid Norway</b>									
Berg	Firm to stiff low sensitive clay	3.6–17.6	23–32	19.8–20.6	n/a	6.6–10.5	39–82	4–10	Rømoe (2006)

**Table 1** (concluded).

Location	Soil type	Depth (m)	w (%)	$\gamma$ (kN/m <sup>3</sup> )	Clay (%)	$I_p$ (%)	$s_u$ (kPa)	$S_t$	References
Rissa H3-H4	Soft to firm clay medium sensitive	2.2–11.1	22–42	18.1–20	37–57	6–14	12–38.5	2–14.1	Gregersen (1981), Aasland (2010), L'Heureux et al. (2011a)
Rissa H5	Soft quick clay	2.4–10.9	28–40	18.3–19.8	47	7–12	9–38	13–61.5	Aasland (2010)
Rødde	Firm silty clay occasionally quick	1.5–20.5	26–33	19.1–19.7	30–47	n/a	28–71	2.5–37 (65–235 occasionally)	Ottesen (2009), Solberg et al. (2011b)
Buvika	Firm quick clay	2.4–23.4	30–39	18.4–19.3	28–47	12–17	20–80	15–350	Solberg et al. (2008), Helle (2004)
<b>North Trøndelag and Northern Norway</b>									
Finnøidfjord	Soft occasionally sandy clay	2.5–11.5	28–40	18.4–21.8	9–17	n/a	12–27	3–11	Lecomte et al. (2008a, 2008b); L'Heureux et al. (2011b)
Kattmarka	Soft silty clay occasionally quick	1.2–19.6	26–38	18.5–19.7	24–35	6–9	9–48	4.8–67	Solberg et al. (2011a), Nordal et al. (2009), Multiconsult (2009)

**Note:** n/a, not available. Additional references: Long et al. (2009); Bjerrum (1967); Lunne and Lacasse (1999); Rømoen (2006); Gregersen (1981); Aasland (2010); Ottesen (2009); Lecomte et al. (2008b); Solberg et al. (2011); Helle (2004); Multiconsult (2009).

ception 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- Hilleren). 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. “Smooth” inversion was generally used as standard (Solberg et al. 2012), but it was found that “robust” inversion can give better definition of sharp boundaries, e.g., between clay and bedrock (Reiser et al. 2010).

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 pre-defined 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).

Resistivity ( $\Omega\cdot\text{m}$ )	Main characterization	Description
1–10	Unleached marine clay deposits	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
10–100	Leached clay deposits	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
>100	Dry crust clay deposits, coarse sediments, (bedrock)	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 $\Omega\cdot\text{m}$ .

den material and to subsequently subject each of the samples to routine index testing as well as more advanced strength and compression tests if these are required. In most of the sites studied here the sampling technique involved use of the NGI 54 mm composite sampler (Andresen and Kolstad 1979), which is the most common sampler used in Norway. It is a composite piston sampler using plastic inner tubes. The displacement method is used, where the sampler is pushed down to the desired depth without pre-augering. Long et al. (2009) describe a detailed study into the quality of samples retrieved using this procedure and demonstrate that the resulting quality is acceptable for routine and medium-sized projects. At a number of sites in the mid Norway region the version of the sampler that uses a thin-walled 54 mm tube only was used.

Index testing normally comprises determination of water content, bulk density, sensitivity using the Swedish fall cone, and unconfined compression testing on all recovered piston samples. A limited number of plasticity, particle density, grain size, salt content, and organic content determinations are also usually made. Specifically, salt content is determined by expelling pore water in a centrifuge and using a correlation between measured electrical conductivity and salinity. Clay (particles less than 0.002 mm in size) and silt (particles between 0.002 and 0.06 mm in size) are determined using either a hydrometer or the falling drop method (Moum 1965). Fall cone testing makes use of the Swedish fall cone. In Norway, fall cone data are interpreted according to NS8015 (Norwegian Standardisation System 1988), which is largely based on the Swedish Geotechnical Institute (SGI 1946) calibration with some local modifications–additions.

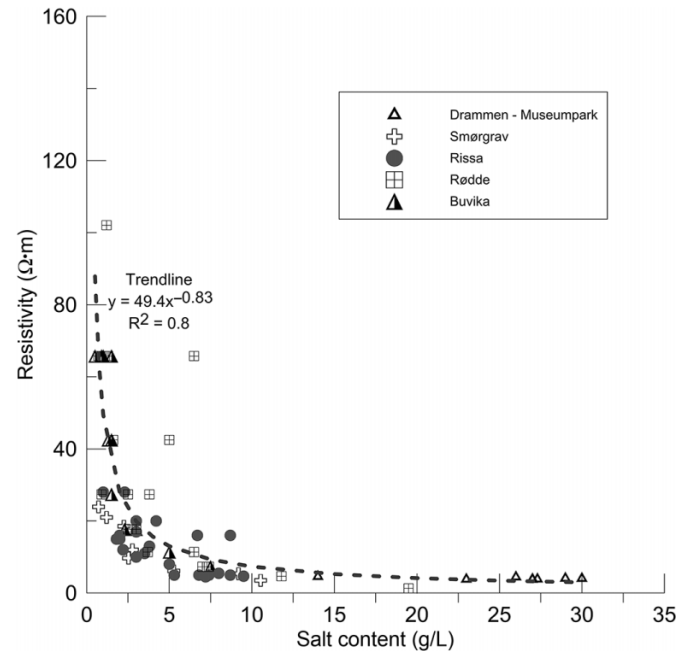
**Results and correlations**

Inverted resistivity values were extracted from the Re<sub>s2D</sub>inv 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

**Fig. 2.** Resistivity and salt content of pore fluid.



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  $\Omega\cdot\text{m}$  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  $s_{ur} < 0.5$  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

Fig. 3. Sensitivity and salt content of the pore fluid.

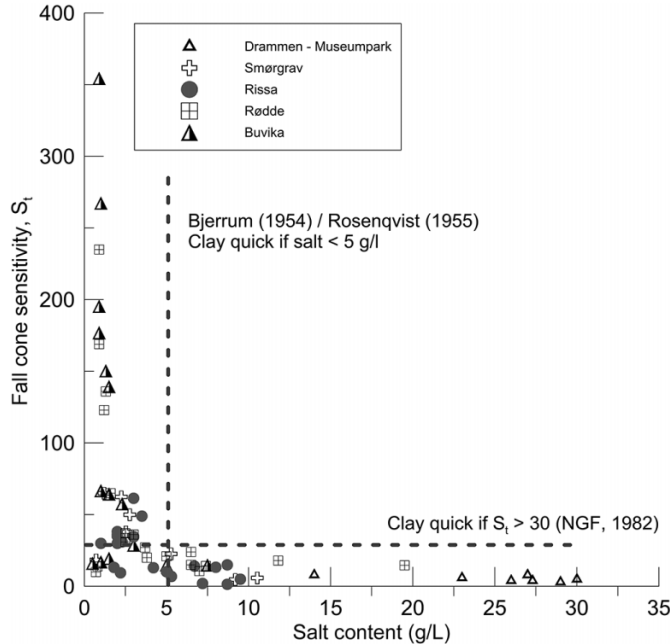
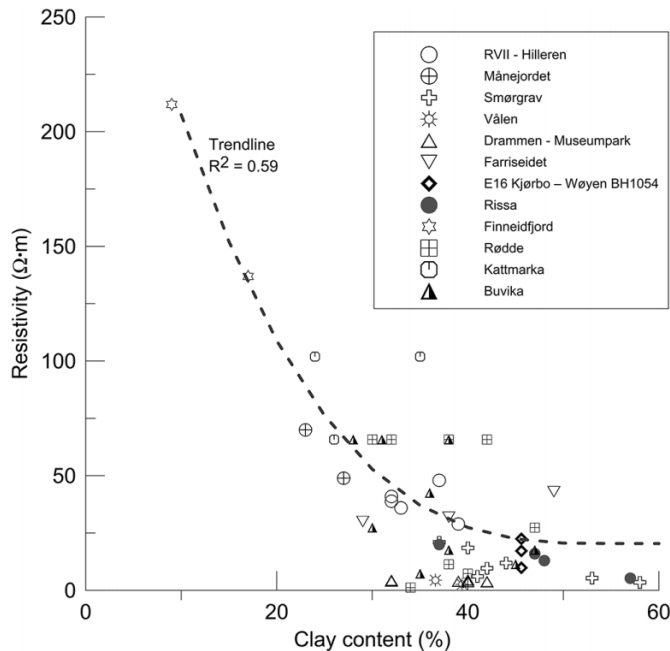


Fig. 4. Resistivity and clay content.



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

Fig. 5. Resistivity and plasticity index.

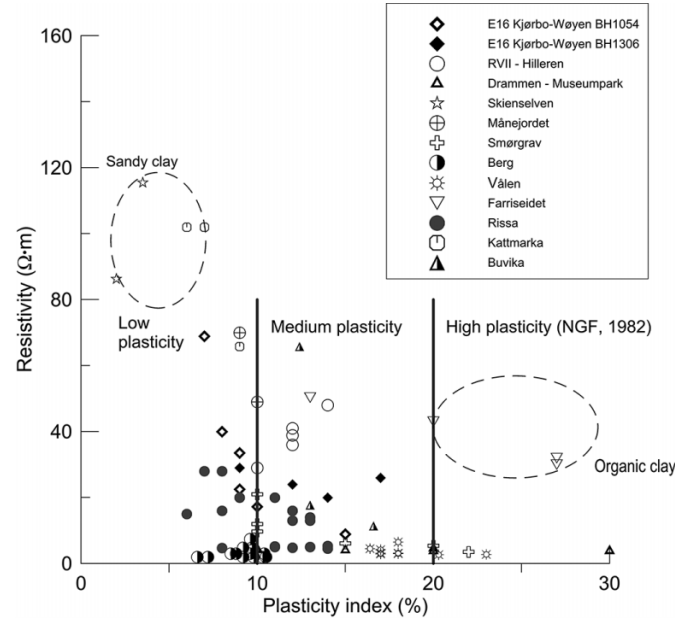
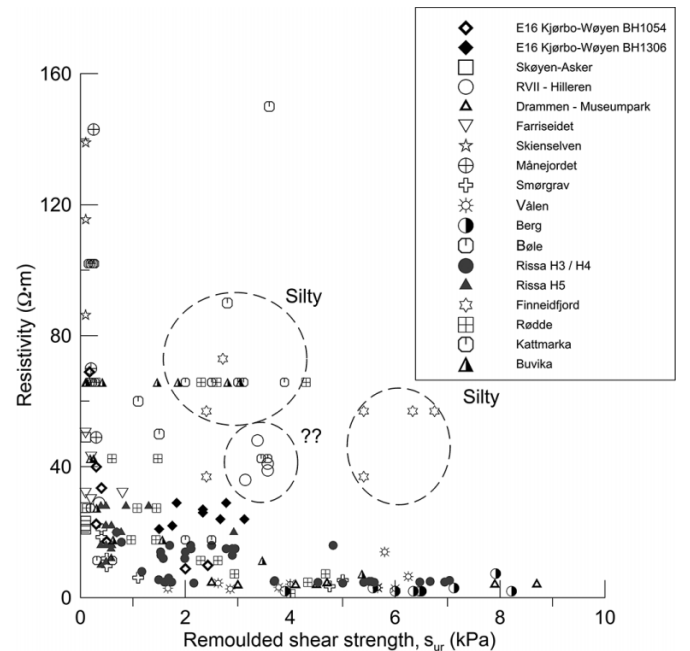


Fig. 6. Resistivity and remoulded shear strength.



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

Fig. 7. Resistivity and remoulded shear strength less than 0.5 kPa.

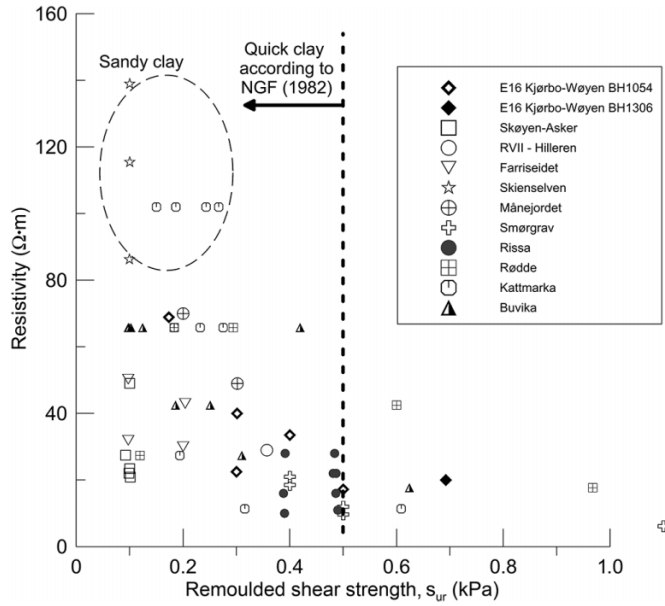
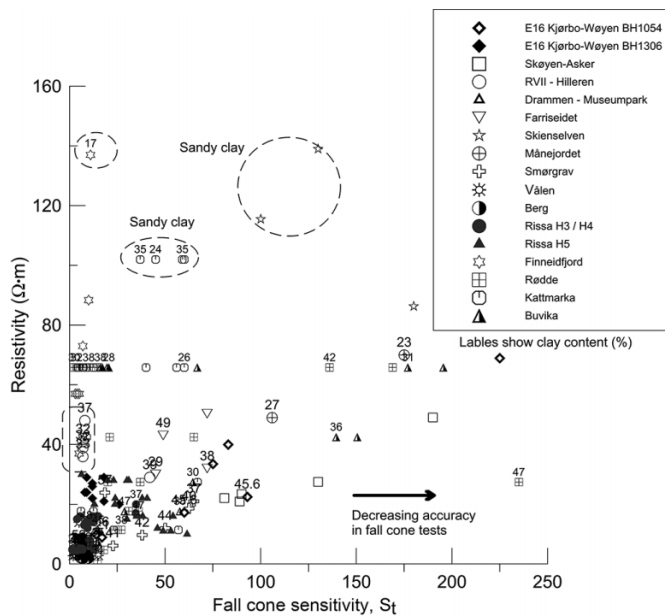


Fig. 8. Resistivity and sensitivity.



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 ( $\approx 5 \Omega\cdot m$ ) 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

Fig. 9. Resistivity and bulk unit weight.

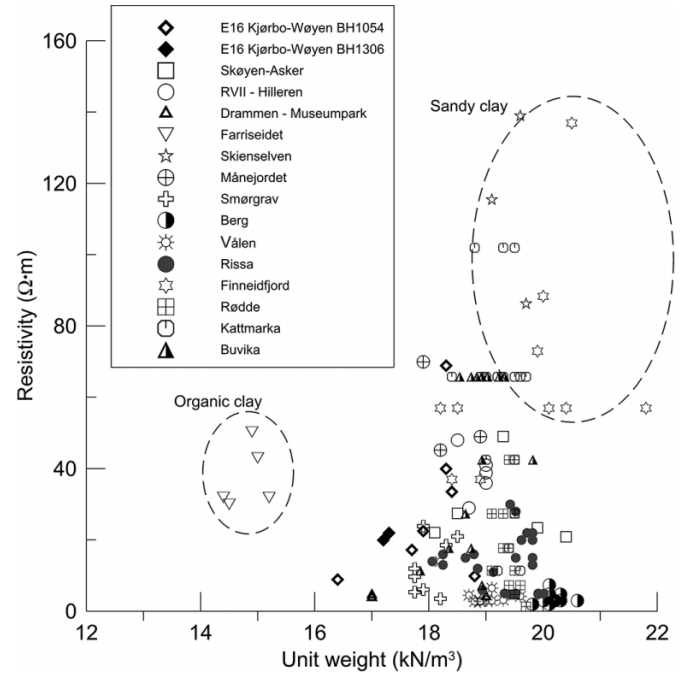
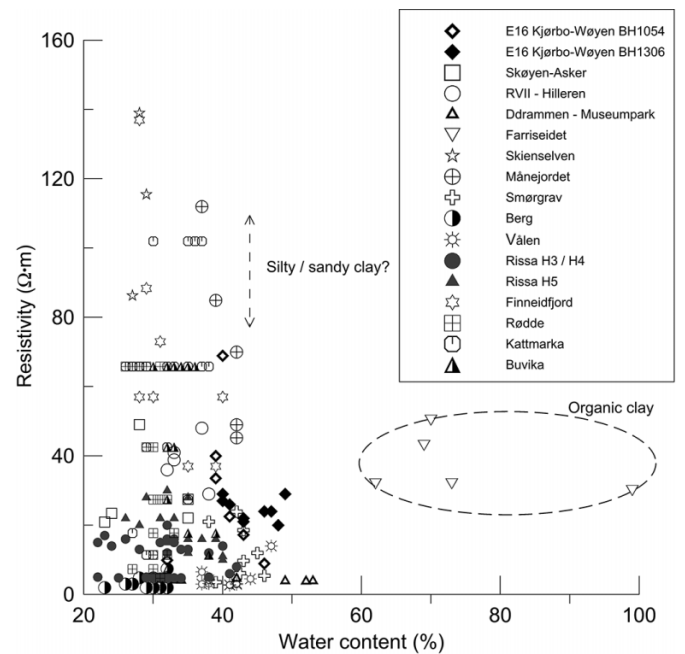


Fig. 10. Resistivity and water content.



trendline through the data, but the resulting  $R^2$  value was poor.

**Resistivity 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 re-



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  $S_t$  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 Smørgrav 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 Farriseidet 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.

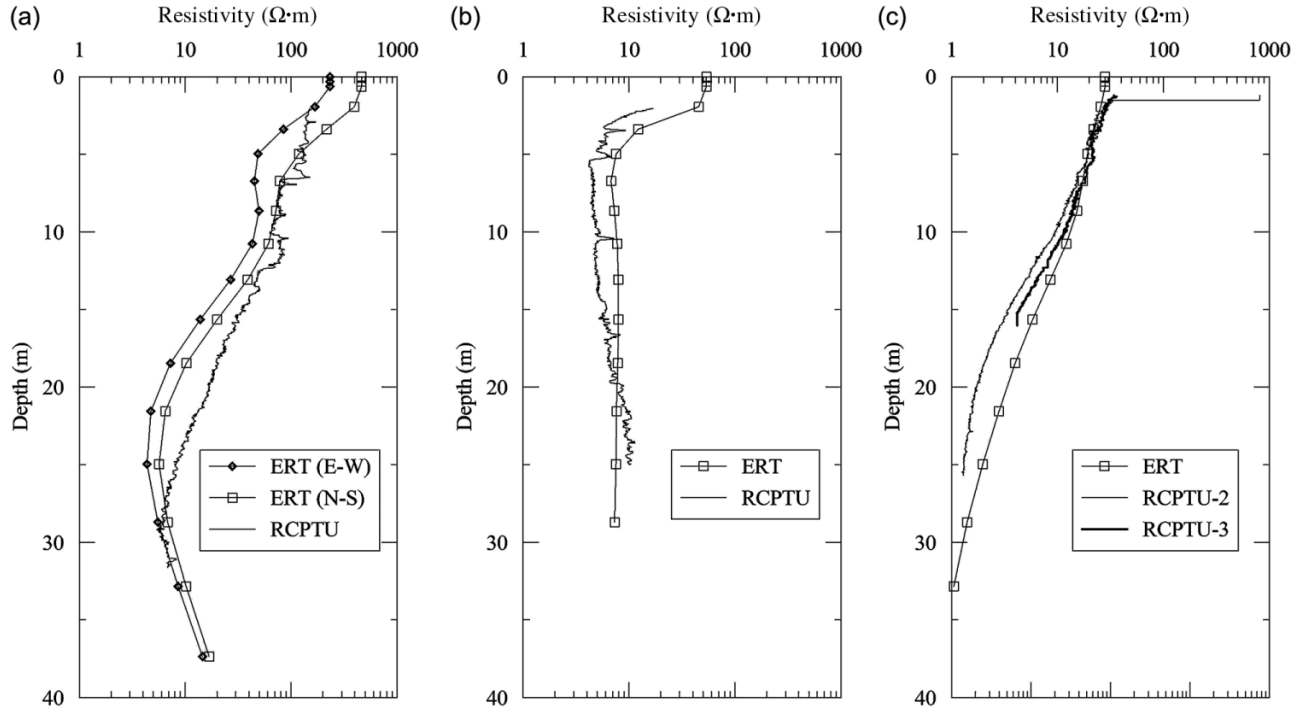
For the data available, no relationship was found between resistivity and water content. However as the range of values studied here is relatively limited, and many other studies have shown the importance of water content on measured resistivity, this finding will not be universally applicable.

### 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.

**Fig. 11.** Comparison of ERT and RCPTU for (a, b) Rissa and (c) Rødde.



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.

**References**

Aasland, R. 2010. Kartlegging av kvikkleire med 2D resistivitet og RCPT i Rissa. Masteroppgave, Institutt for Geoteknikk. NTNU, Trondheim, Norway. [In Norwegian.]

Andersson-Sköld, Y., Torrance, J.K., Lind, B., Odén, K., Stevens, R. L., and Rankka, K. 2005. Quick clay - A case study of chemical perspective in southwest Sweden. *Engineering Geology*, **82**(2): 107–118. doi:10.1016/j.enggeo.2005.09.014.

Andresen, A., and Kolstad, P. 1979. The NGI 54mm samplers for undisturbed sampling of clays and representative sampling of coarser materials. *In Proceedings of the International Symposium on Soil Sampling*, Singapore. pp. 13–21.

Bjerrum, L. 1954. Geotechnical properties of Norwegian marine clays. *Géotechnique*, **4**(1): 49–69.

Bjerrum, L. 1967. Engineering geology of Norwegian normally consolidated marine clays as related to settlement of buildings. *Géotechnique*, **17**(2): 81–118.

Dahlin, T. 1993. On the automation of 2D resistivity surveying for engineering and environmental applications. Ph.D. thesis, Department of Engineering Geology, Lund University of Technology, Sweden.

Dahlin, T., and Zhou, B. 2006. Multiple-gradient array measurements for multi-channel 2D resistivity imaging. *Near Surface Geophysics*, **4**: 113–123.

Dahlin, T., Palm, M., and Garin, H. 2004. Combined resistivity imaging and RCPT for geotechnical preinvestigation. *In Proceedings of the 14th NGM, Nordic Geotechnical Meeting*, Ystad, Sweden. pp. C81–C88.

Dahlin, T., Larsson, R., Leroux, V., and Rankka, K. 2005. Resistivity imaging for mapping of quick clays for landslide risk assessment. *In Proceedings of Near Surface 2005 – 11th European Meeting of Environmental and Engineering Geophysics*, Palermo, Italy.

Donohue, S., Long, M., O'Connor, P., Eide-Helle, T., Pffaffhuber, A. A., and Rømøen, M. 2011. Geophysical mapping of quick clay: a case study from Smørgrav, Norway. *Near Surface Geophysics*, [In press.]

Fukue, M., Minato, T., Horibe, H., and Taya, N. 1999. The microstructures of clay given by resistivity measurements. *Engineering Geology* **54**(1–2): 43–53. doi:10.1016/S0013-7952(99)00060-5.

Geertsema, M., and Torrance, J.K. 2005. Quick clay from the Mink Creek landslide near Terrace, British Columbia: Geotechnical properties, mineralogy, and geochemistry. *Canadian Geotechnical Journal*, **42**(3): 907–918. doi:10.1139/t05-028.

Gregersen, O. 1981. The quick clay landslide at Rissa, Norway. Norwegian Geotechnical Institute Publication 135. Norwegian Geotechnical Institute. pp. 1–6.

Helle, T.E. 2004. E39 Vigda, Buvika, Profile 3 - Natural Slope. Projectoppgave, Institutt for Geoteknikk. NTNU, Trondheim, Norway.

L'Heureux, J.-S., Eilertsen, R.S., Glimsdal, S., Issler, D., Solberg, I.-L., and Harbitz, C.B. 2011a. The 1978 quick clay landslide at Rissa, mid Norway: subaqueous morphology and tsunami simulations. *In Proceedings of the 5th International Symposium on Submarine Mass Movements and Their Consequences. Edited by Y. Yamada et al.*, Kyoto, Japan. Springer Science + Business Media.

L'Heureux, J.-S., Longva, O., Steinar, A., Hansen, L., Vardy, M.E., Vanneste, M., et al. 2011b. Identification of weak layers and their

role for the stability of slopes at Finneidfjord, Northern Norway. *In Proceedings of the 5th International Symposium on Submarine Mass Movements and Their Consequences. Edited by Y. Yamada et al.* Kyoto, Japan. Springer Science + Business Media. pp. 321–330.

Lecomte, I., Bano, M., Hamran, S.-E., Dalsegg, E., and Nielsen, K. M. 2008a. Mapping quick clay sites for geohazard assessment: the Finneidfjord case study, Norway. *In Proceedings of Near Surface 2008 - 14th European Meeting of Environmental and Engineering Geophysics*, Kraków, Poland. Paper B19.

Lecomte, I., Bano, M., Hamran, S.-E., Dalsegg, E., Nielsen, K.M., Nielsen, M.H., et al. 2008b. Submarine slides at Finneidfjord (Norway): geophysical investigations. *In Proceedings of the 21st EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems*. pp. 376–388.

Löfroth, H., Suer, P., Dahlin, T., Leroux, V., and Schälin, D. 2011. Quick clay mapping by resistivity - Surface resistivity, CPTU-R and chemistry to complement other geotechnical sounding and sampling. *IN Statensgeotekniskainstitut, SGI. Götaålvutredningen. GÅU. Delrapport 30. Swedish Geotechnical Institute, Linköping, Sweden.*

Loke, M.H. 2007. Res2DInv ver. 3.56. Geoelectrical imaging 2D and 3D. Instruction manual. Geotomo Software.

Loke, M.H., and Barker, R.D. 1996. Rapid least-squares inversion of apparent resistivity pseudosections by quasi Newton method. *Geophysical Prospecting*, **44**(1): 131–152. doi:10.1111/j.1365-2478.1996.tb00142.x.

Loke, M.H., and Dahlin, T. 2002. A comparison of Gauss-Newton and quasi Newton methods in resistivity imaging inversion. *Journal of Applied Geophysics*, **49**(3): 149–162. doi:10.1016/S0926-9851(01)00106-9.

Long, M., El Hadj, N., and Hagberg, K. 2009. Quality of conventional fixed piston samples of soft clay. *Journal of Geotechnical and Geoenvironmental Engineering*, **135**(2): 185–198. doi:10.1061/(ASCE)1090-0241(2009)135:2(185).

Longva, O., Janbu, N., Blikra, L.H., and Bøe, R. 2003. The 1996 Finneidfjord slide: seafloor dynamics. *In Proceedings of the 1st International Symposium on Submarine Mass Movements and their Consequences, EGS-AGU-EUG Joint Meeting*. Nice, France. Kluwer Academic Publishers. pp. 531–538.

Lundström, K., Larsson, R., and Dahlin, T. 2009. Mapping of quick clay formations using geotechnical and geophysical methods. *Landslides*, **6**(1): 1–15. doi:10.1007/s10346-009-0144-9.

Lunne, T., and Lacasse, S. 1999. Geotechnical characterisation of the low plasticity Drammen clay. *In Proceedings of the International Symposium on Characterisation of Soft Marine Clays - Bothkennar, Drammen, Quebec and Ariake clays. Edited by T. Tsuchida and A. Nakase.* Yokosuka: A.A. Balkema, Rotterdam. pp. 33–56.

Mitchell, J.K. 1993. *Fundamentals of soil behavior*. Wiley, New York.

Mitchell, J.K., and Soga, K. 2005. *Fundamentals of Soil Behaviour*. John Wiley and Sons, Hoboken, New Jersey.

Moum, J. 1965. Falling drop used for grain-size analysis of fine grained materials. *Sedimentology*, **5**(4): 343–347. doi:10.1111/j.1365-3091.1965.tb01566.x.

Multiconsult. 2009. Kattmarken boligfelt, grunnundersøkelser. Geoteknisk datarapport med orienterende geoteknisk vurdering. Multiconsult Report No. 413456–1, dated 06.03.2009. [In Norwegian.]

NGF. 1982. Veilding for symboler og definisjoner i goeteknikk - presentasjon av geotekniske undersøkelser. Norwegian Geotechnical Society (Norsk Geoteknisk Forening), Oslo. [In Norwegian.]

Nordal, S., Alén, C., Emdal, A., Jendebu, L., Lyche, E., and Madhusu, C. 2009. Skredet i Kattmarkvegen i Namsos 13. mars 2009. Rapport fra undersøkelsesgruppe satt ned av Samferdselsdeparte-

- mentet. Institutt for Bygg, Anlegg og Transport, Faggruppe for Geoteknikk, NTNU. [In Norwegian.]
- Norwegian Standardisation System. 1988. Falling cone tests. Standard NS 8015. Norwegian Standardisation System, Oslo, Norway.
- Ottesen, H.B. 2009. CPTU med resistivitetsmåling. Masteroppgave, Institutt for Geoteknikk. NTNU, Trondheim, Norway. [In Norwegian.]
- Pfaffhuber, A.A., Bastani, M., Cornèe, S., Rømoen, M., Donohue, S., Helle, T.E., et al. 2010. Multi - method high resolution geophysical and geotechnical quick clay mapping. *In Proceedings of Near Surface 2010 - 16th European Meeting of Environmental and Engineering Geophysics*, Zurich.
- Reiser, F., Dahlin, T., Rønning, J.S., and Solberg, I.-L. 2010. Resistivity modelling for clay layer characterisation, possibilities and limitations. Geological Survey of Norway (NGU), Trondheim, Norway. Report 2010.047.
- Reynolds, J.M. 2011. An introduction to applied and environmental geophysics. Wiley - Blackwell, UK.
- Rømoen, M. 2006. Evaluation of stability and deformations in the Berg area Trondheim. Masteroppgave, Institutt for Geoteknikk. NTNU, Trondheim.
- Rømoen, M., Pfaffhuber, A.A., Karlsrud, K., and Helle, T.E. 2010. "Resistivity on marine sediments retrieved from RCPTU soundings: a Norwegian case study. *In Proceedings of the 2nd International Symposium on Cone Penetration Testing (CPT '10)*. Edited by P.K. Robertson and P.W. Mayne. Omnipress, Huntington Beach, California. pp. 289–296.
- Rosenqvist, I.T. 1955. Investigations in the clay-electrolyte-water system. Norwegian Geotechnical Institute Publication 9. Norwegian Geotechnical Institute.
- Sauvin, G., Bazin, S., Vanneste, M., Lecomte, I., and Pfaffhuber, A. A. 2011. Towards joint inversion / interpretation for landslide-prone areas in Norway - integrating geophysics and geotechnique. *In Proceedings of Near Surface 2011 - 17th European Meeting of Environmental and Engineering Geophysics*. Leicester, UK. Paper E11.
- Schälin, D., and Tornborg, J. 2009. Evaluation of CPT-R and resistivity measurements in quick clay area. M.Sc. thesis, Department of Civil and Environmental Engineering, Division of GeoEngineering, Chalmers University of Technology, Göteborg, Sweden.
- SGI. 1946. Korfattat compedium i geoteknikk Meddelande Nr. 1. Swedish Geotechnical Institute, (SGI), Stockholm. [In Swedish.]
- Solberg, I.-L., Rønning, J.S., Dalsegg, E., Hansen, L., Rokoengen, K., and Sandven, R. 2008. Resistivity measurements as a tool for outlining quick-clay extent and valley-fill stratigraphy: a feasibility study from Buvika, central Norway. *Canadian Geotechnical Journal*, **45**(2): 210–225. doi:10.1139/T07-089.
- Solberg, I.-L., Aasland, R., Dalsegg, E., Hansen, L., L'Heureux, J.-S., and Rønning, J.S. 2010. Kvikkleireproblematikk i Rissa - bruk av resistivitetsmålinger. Fjellsprengningsdagen, Bergmekanikk- og Geoteknikkdagen. Norsk Geoteknisk Forening, Oslo, Norway. Chapter 37. [In Norwegian.]
- Solberg, I.-L., Dalsegg, E., and Hansen, L. 2011. Resistivitetsmålinger for løsmassekartlegging i Namsos, Nord-Trøndelag. Data og tolkninger Geological Survey of Norway (NGU), Trondheim, Norway. Report 2010.046. [In Norwegian.]
- Solberg, I.-L., Hansen, L., Rønning, J.S., Haugen, E.D., Dalsegg, E., and Tønnesen, J.F. 2012. Combined geophysical and geotechnical approach to ground investigations and hazard zonation of a quick clay area, mid Norway. *Bulletin of Engineering Geology and the Environment*, **71**(1): 119–133. doi:10.1007/s10064-011-0363-x.
- Torrance, J.K. 1974. A laboratory investigation of the effect of leaching on the compressibility and shear strength of Norwegian marine clays. *Géotechnique*, **24**(2): 155–173. doi:10.1680/geot.1974.24.2.155.
- Torrance, J.K., and Ohtsubo, M. 1995. Ariake Bay quick clays: A comparison with the general model. *Soils and Foundations*, **35**(1): 11–19. doi:10.3208/sandf1972.35.11.