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3	In sentence 'On average …' Table 3 is cited out of sequence. Please mention Table 2 somewhere before this point and after reference to Table 1 (or delete this citation of Table 3)
4	In sentence 'Smørgrav is possibly …' please confirm change to 'possibly the only site' is correct (or 'one of the few sites'?)
5	Amundsen et al. 2015a - please add book editor/s, publisher's name + city, and page numbers of paper
6	Andresen & Kolstad 1979 - please add book editor/s and publisher's name + city
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18	Helle et al. 2017b - please add page numbers of paper
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23	L'Heureux et al. 2011 - please give names of book editors
24	Longva et al. 2003 - please add book editor/s

25	Lunne et al. 2003 - please add book editor/s
26	Pfaffhuber et al. 2010 - please add book editor/s, publisher’s name + city, and page numbers of paper
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28	Sandven et al. 2004 - please add book editor/s
29	Sauvin et al. 2011 - please add book editor/s, and publisher’s name + city
30	Sauvin et al. 2013a - please add book editor/s, publisher’s name + city, and page numbers of paper
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35	Table 3, site 10 - please check values are in the correct columns

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Glacio-marine clay resistivity as a proxy for remoulded shear strength: correlations and limitations

Q1

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Abstract: In geotechnical engineering in Norway, Sweden and Canada the presence of sensitive and/or quick clays poses a major challenge. Formation of these clays involves the leaching of salt from the pore fluid. Thus it has been recognized that electrical resistivity measurements could be useful in delineating leached and unleached clays. This paper seeks to assess the applicability, repeatability and reliability of the various geophysical techniques in the study of sensitive clays. It also attempts to understand the factors that control the measured resistivity and in particular to determine the limitations of directly obtaining the remoulded shear strength from the resistivity measurements. It was found that borehole, surface and airborne resistivity measurements are accurate and compatible. For the 30 Norwegian sites studied it was found that resistivity is primarily defined by the porewater salt content, with minor additional influence by clay content and plasticity, and porosity. A relationship exists between resistivity and remoulded shear strength but this is limited to material deeper than the dry crust and a surface weathering zone of about 7.5 m thickness. High resistivity (>10 Ω m) may indicate quick or weathered clay but low resistivity (<10 Ω m) conclusively points to stable, unleached clay.

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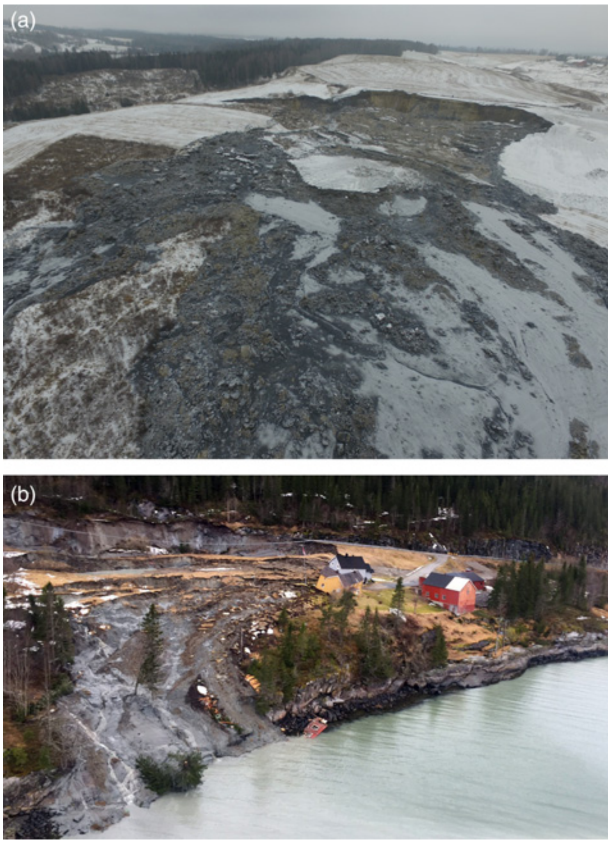
Sensitive glacio-marine clays, so called quick clays, are typically found in Norway, Sweden and Canada (there often referred to as Leda or Champlain Sea clays), and are characterized by a remoulded undrained shear strength (c_{ur}) that is considerably lower than the intact undisturbed shear strength (c_u). In geotechnical engineering the presence of sensitive clays poses a major challenge. The landslide at Rissa in 1978 (Gregersen 1981) is perhaps the most famous quick clay slide, as the sliding action was captured on camera. More recently in Norway the slides at Tosbotn in April 2016 and Sørum in November (Fig. 1), are devastating reminders of the potential threats related to such soils. The Tosbotn slide carried away three houses and cut the only road connecting Brønnøysund (population *c.* 5000) with the mainland, forcing all traffic onto ferries. At Sørum three forestry workers were killed by the slide, which encapsulated an area of 270 m × 420 m and had a runout distance of some 1 km. For the geotechnical engineer in a construction project, or during regional or local hazard assessment, it is hence important to determine if there is sensitive clay present and, if there is, to determine the extent of the deposit.

The Scandinavian post-glacial marine clays were deposited in a marine environment during and after the last ice age some 10 000 years ago, entrapping porewater of high salt content in the voids. Leaching of the porewater by meteoric groundwater flow has diluted the porewater salinity in some clays. Without its salt, the clay structure can easily collapse and the clay becomes quick. According to the Norwegian definition quick clay is one in which c_{ur} is less than 0.5 kPa (NGF 2011). The most reliable method to confirm quick clay is sampling and index testing in the laboratory to measure c_{ur} and sensitivity ($S_t = c_u/c_{ur}$). However, these tests are costly for systematic quick clay hazard zonation.

The electric resistivity method goes back as far as the early 20th century and was primarily developed to distinguish oil-bearing from water-bearing layers (Archie 1942). In general, resistivity (the ability to conduct electrical current) of soils and rocks is a function of Q2 porosity, the ion content or salinity of the porewater, clay content, and the presence of charged minerals such as graphite and some sulphides (see, e.g. Rhoades *et al.* 1976; Palacky 1987). For clays in general, and for leached clays in particular, it is mainly the salt content that influences the resistivity (Shevnin *et al.* 2007). The resistivity is normally higher in leached clay than in the intact marine clays. By measuring the soil resistivity, one may hence be able to deduce the potentially leached zones. Results from Canada, Sweden and Norway clearly point towards a relationship between the geotechnical sensitivity and the measured resistivity. Aylsworth & Hunter (2004) showed the resistivity contrast between leached and saline Leda clay, Dahlin *et al.* (2013) described comparable studies based on quick clay in Sweden, and Rømoen *et al.* (2010) gave resistivity ranges for various Norwegian soil types (and their significant overlap). Based on a number of Norwegian sites, Solberg *et al.* (2012) suggested a classification scheme (see Table 1), a simplified approach that may be applied for a confined region with consistent sedimentation history.

With these principles in mind resistivity measurements have been carried out, using several different techniques, in a significant number of Norwegian marine clay sites over recent years. This paper will review the methods used, assess whether repeatable and reliable values of resistivity can be obtained, evaluate the scale effects and zone of influence pertaining to each of the methods, and determine the usefulness of the techniques in quick clay mapping projects. This will be achieved by assembling data from 30 sites, comparing the results from several methods and examining which parameters control the measured resistivity.

First, some characteristics of a typical Norwegian quick clay site will be presented, followed by a short discussion on the geochemistry of quick clay.



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Q31 **Fig. 1.** Recent 2016 landslides in quick clay. (**a**) Tosbotn slide, April 2016, showing damaged houses and the blocked regional road in the background (photograph: Ole-Christian Olsen, Norwegian Broadcasting Corporation/NRK; Brønnøy skred_Tosbotn_Ole-Christian Olsen_NRK. jpg). (**b**) Sørum slide, November 2016

Table 1. *Classification of Norwegian marine clays according to resistivity value (Solberg et al. 2012)*

Material	Resistivity range (Ω m)
Unleached marine clay	1 – 10
Leached, possibly quick clay	10 – 80/100
Dry crust clay, slide deposits, coarser material such as sand and gravel, and bedrock	>100

Example of typical Norwegian quick clay site

The Tiller quick clay research site, located just south of Trondheim, has been used by researchers at the Geotechnical Division of the Norwegian University of Science and Technology (NTNU, formerly NTH) for research purposes for many years. Full details of the geotechnical properties of the Tiller site have been given by Gylland *et al.* (2013). For the site, average water content (w) is about 36%, unit weight (γ) is 18.7 kN m^{-3} and clay content is some 36%, and these parameters remain reasonably constant with depth (Fig. 2). On average, the plasticity index (I_p) is about 5% (Table 3), and is perhaps a little lower in the quick clay zone. Q3 Details of the measured S_t, c_{ur} and salt content values are also given in Figure 2. It can be seen that the site comprises *c.* 8 m of low-sensitivity clay over quick clay. Despite the clear distinction between the low-sensitivity clay and quick clay at about 8 m depth, the salt content of the pore fluid remains more or less constant throughout the profile, with an average value of about 1 g l^{-1}. Considering that the material was deposited in marine conditions, it is clear that the material has been leached throughout the profile. This finding, which is common for many Norwegian sites, poses a significant challenge in using resistivity to distinguish between non-quick clays that have been 'over-leached' and those that have been leached and are also quick, as both have a similar resistivity. This is generally a shallow phenomenon and further examples (e.g. Fig. 3)

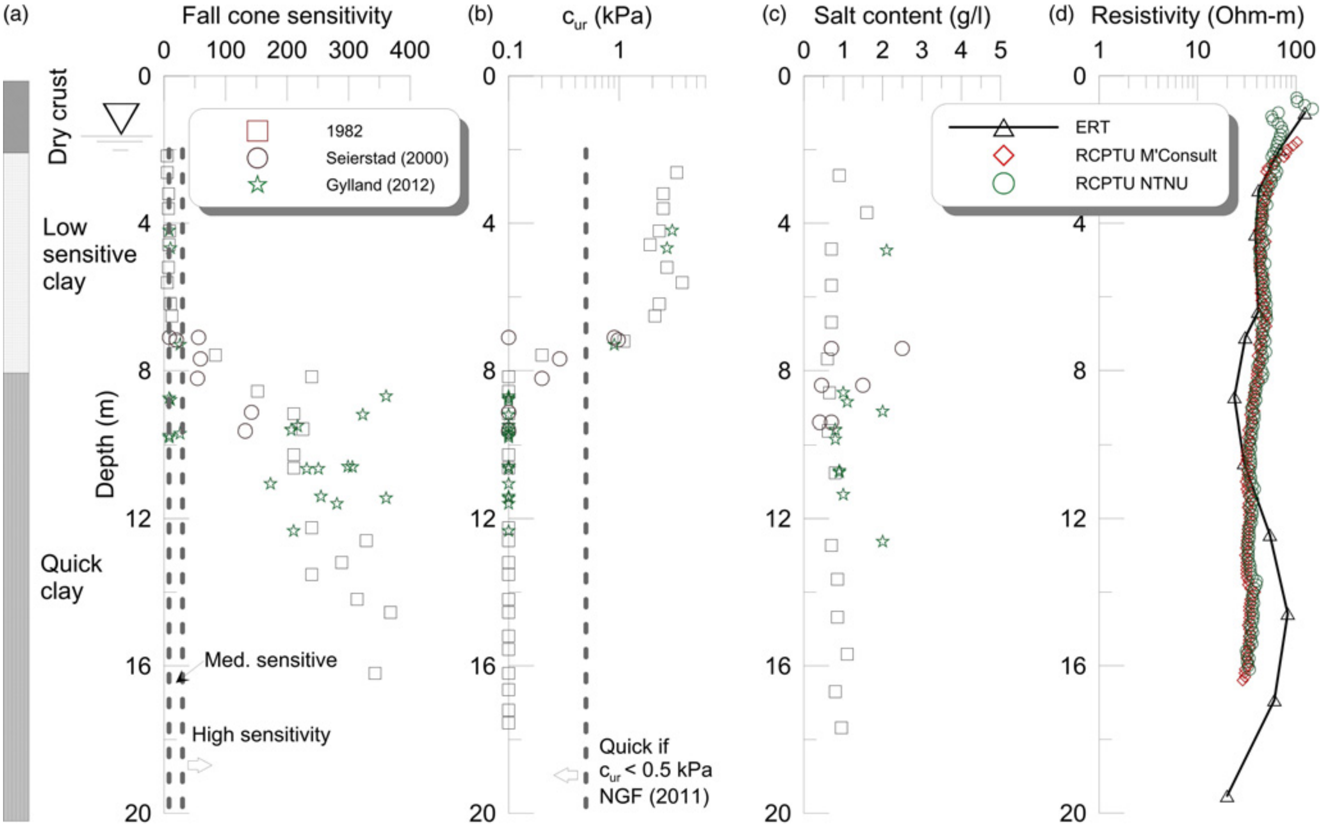

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Fig. 2 Tiller site: (**a**) sensitivity; (**b**) remoulded shear strength; (**c**) salt content; (**d**) resistivity.

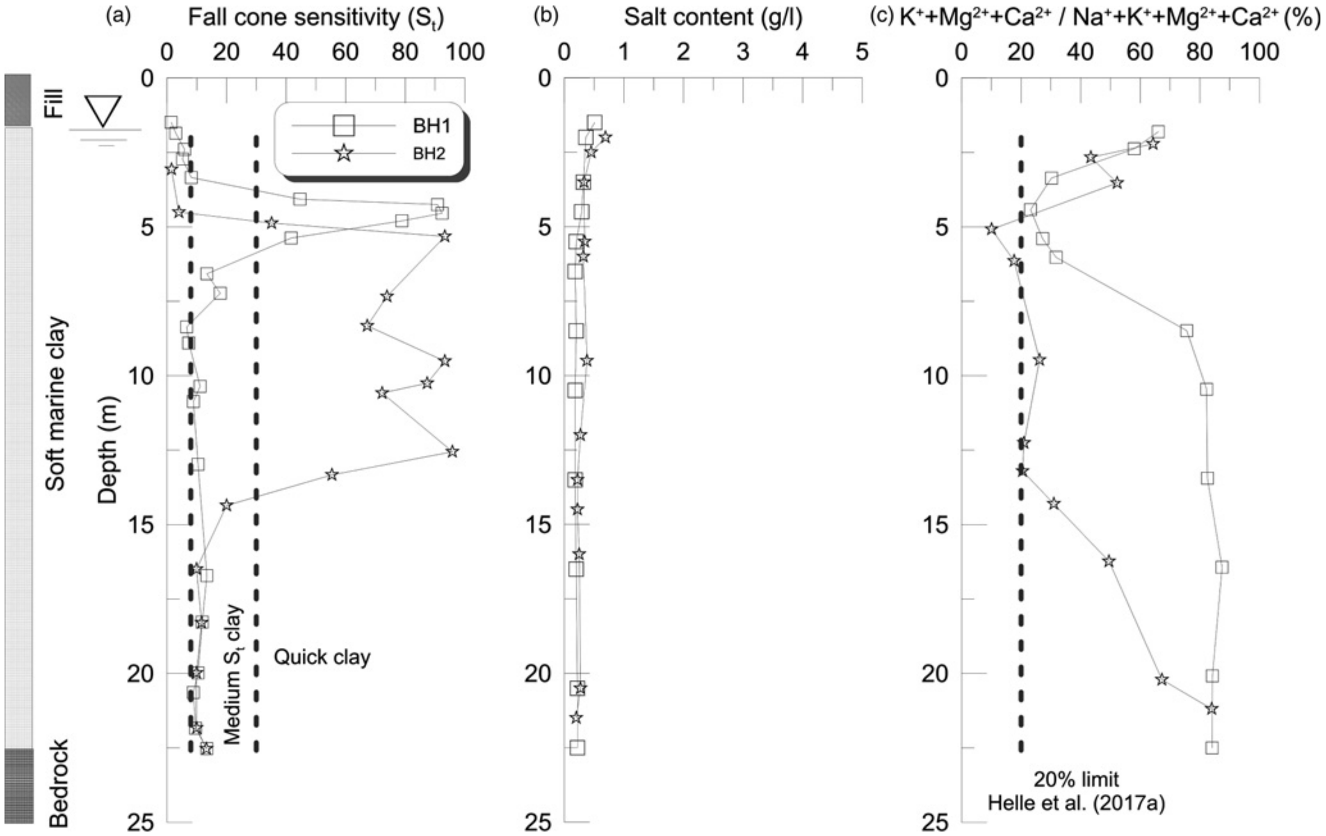

Fig. 3. Tinghuset site, Drammen: (**a**) S_t; (**b**) salt content; (**c**) ion content of porewater (Moum *et al.* 1971, 1972).

show the clearly lower resistivity of deeper, unleached clay units. Some further explanation of the nature of leached yet non-quick clays is given in the following.

Geochemistry of marine clays

The salt content in the depositional environment for the Scandinavian clays may have been in the range 30 – 35 g l^{-1} and was highly dominated by sodium (Na^+) and chloride (Cl^-) (see, e.g. Moum *et al.* 1971; Appelo & Postma 2005; Mitchell & Soga 2005). Na^+ is the abundant ion both in the porewater and in the adsorbed positions on the mineral surface in clays sedimented in the glacio-marine environment. This high salt content suppresses the diffuse double-layer surrounding the clay minerals, resulting in low repulsive forces and a stable structure.

Following isostatic uplift groundwater can migrate through the clay deposits, diluting and changing the ion composition in the porewater. Flowing groundwater is often dominated by divalent ions such as magnesium (Mg^{2+}) and calcium (Ca^{2+}), both of which are preferred over Na^+ by the mineral surface (Mitchell & Soga 2005). As Mg^{2+} and Ca^{2+} are absorbed onto the mineral surface Na^+ is released into the pore fluid. The salt content is now reduced and thus the thickness of the diffuse double-layer increases, which in turn leads to a rise in the repulsive forces between the clay particles (see, e.g. Penner 1965; van Olphen 1977; Torrance 1983). The material now has a low c_{ur}, a high S_t, is easier to remould and may even be quick.

Leaching is a continuing process; more and more divalent ions enter the clay–water system and thus the concentration of Na^+ in the porewater is further depleted. These divalent cations have a greater impact on the double-layer thickness than the monovalent cations at the same concentration (see, e.g. Helle *et al.* 2017*a*, 2017*b*). The salt content is still low but the divalent ions suppress the diffuse double-layer and the repulsive forces now decrease, thus gradually again increasing c_{ur} and reducing S_t. It is also for this reason that the geotechnical properties of quick clays can be improved by treatment with potassium chloride (KCl). K^+ is preferred over Na^+ by the mineral surface and thus has a greater effect in suppressing the diffuse double-layer and reducing the repulsive forces. Eggestad & Sem (1976) and Helle *et al.* (2015, 2016) have shown how introducing KCl by salt wells improved the characteristics of quick clays at the Ulvensplitten and Dragvoll sites in Norway.

Helle *et al.* (2017*a*) suggested that the clay behaviour changes from quick to non-quick at the threshold value of 20% of the ratio of the sum of K^+, Mg^{2+} and Ca^{2+} to the major cations. An example of this idea applied to the Tinghuset site in Drammen, Norway (Moum *et al.* 1971, 1972) is shown in Figure 3. At this site two boreholes 25 m apart showed distinctly different conditions. BH1 had a 3 m zone of quick clay, whereas BH2 had a 10 m quick clay zone (Fig. 3a). However, both had leached clay with very low salt content throughout the sequence (Fig. 3b). The ratio of the sum of K^+, Mg^{2+} and Ca^{2+} to that of the major cations, that is, $(K^+ + Mg^{2+} + Ca^{2+})/(Na^+ + K^+ + Mg^{2+} + Ca^{2+})$, is 20% or less over the quick clay zone in both boreholes (Fig. 3c). An understanding of the geochemistry of marine clays is clearly a key to identifying quick clay zones.

Study sites

A summary of the sites studied as part of this work is given in Tables 2 and 3. The reader is referred to the references given in Table 2 for further details of the sites. The sites are distributed over Norway's most populated, quick clay prone areas in South East and Central Norway (Fig. 4). The sites 1–11 in SE Norway are located in the counties Østfold, Akershus, Buskerud, Vestfold and Telemark, and the Central Norwegian sites, 12–30, are in Trondheim, Sør Trøndelag and Nor Trøndelag. Some soil properties at the study sites are summarized in Table 3. In general, the sites are all underlain by soft or medium stiff lightly overconsolidated slightly silty clays. The range of the measured soil properties is relatively

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Q32 **Fig. 4.** Map showing location of study sites in Norway. (Jean-Seb.)

narrow, with w and γ values being typically in the ranges 30 – 45% (mean about 33%) and 1.8 – 2.0 Mg m^{-3} respectively. Clay content is relatively high, being typically 30 – 45% (mean at 35%), and I_p is more or less always less than 20% and frequently less than 10%. S_t values vary widely.

Resistivity techniques

A detailed description of the techniques used in this study to measure resistivity in geotechnical boreholes, from the surface and from the air, has been given by Pfaffhuber *et al.* (2016) and these techniques are briefly summarized as follows.

Resistivity cone testing (RCPTU)

The sounding equipment used for RCPTU consists of an ordinary piezocone (CPTU) probe and a resistivity module mounted behind the probe. Scandinavian manufacturers of RCPTU equipment have chosen to equip their resistivity probes with four ring-electrodes. The two outer electrodes transmit electric current into the soil, whereas the two inner electrodes measure the difference in potential. The electrodes need to be in contact with the soil volume where the measurements take place. The module is powered by batteries, and it can read, store and transmit measured data acoustically through the rods or via an electric cable to a receiver on the surface. The measured data can also be stored on a digital memory-card mounted in the probe. The resistivity depth profile is limited only by the maximum borehole penetration depth (of the order of 50 – 70 m). The module needs to be regularly calibrated in brine solutions of salt and water to ensure correct readings.

Electrical resistivity tomography (ERT)

ERT is a geophysical ground imaging method in which DC electrical current is injected into the ground via short steel electrodes installed 10 – 20 cm into the ground. By measuring the differences in electric potential at the ground surface, a measure of the soil resistance is obtained for all electrode locations or a combination of electrode pairs. Typically electrode spacing varies between 2 and 4 m for high-resolution surveys that are needed for quick clay investigations. The measuring profiles are organized in one or more straight lines. Use was made of both the Wenner and Gradient array systems. The Gradient array uses a large number of potential electrode combinations scanning across the electrode layout and 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 & Zhou 2006). Present-day equipment can measure potentials on several parallel channels and the total time required for measurements in a profile is under 1 h. The investigation depth is defined by the maximum distance between the current and potential electrodes, and the resolution is defined by the electrode spacing. Generally the investigation depth will be 10 – 20% of the profile length, depending on the resistivity distribution in the soil. By processing the data and running an inversion algorithm, a 2D or 3D or even 4D resistivity model of the ground can be obtained. The software RES2DINV was used to invert all of the ERT data acquired in this study. Details of the processing method have been given by Loke & Barker (1996) and Loke (2016). Usually resistivity is gradually increased or decreased laterally and in depth until the model fits the data, leading to a smooth resistivity model. There exists no unique resistivity model for an ERT measurement, and use of different calculation models can illustrate the uncertainty (Bazin & Pfaffhuber 2013).

Airborne electromagnetics (AEM)

AEM measurements are used to map the electrical resistivity of the ground in a larger area. The sensor (antenna) of the AEM equipment is operated at a height of about 30 m above the ground surface, and is usually lifted by a helicopter. Modern airborne systems have sufficient resolution to allow use in geotechnical applications. Different AEM systems are available, some adapted to the need for large penetration depths for mineral exploration, others for more shallow applications in hydrogeology and geotechnical engineering. All systems have in common that a magnetic field generated by the antenna induces current in the ground, which propagates downward and outwards. The rate of change in the electromagnetic field produced by these currents is recorded by a secondary coil. By inversion of the measured data points, the resistivity distribution in the ground can be modelled. Interpretation of AEM resistivity data with regard to sediment properties has so far been done manually and is an advanced task. The possible investigation depth may vary from 50 m to about 500 m, depending on the geology and type of soil in the area, the AEM system and the influence of noise from surrounding infrastructure.

Laboratory resistivity measurements

Both horizontal and vertical (relative to the direction of sampling) laboratory resistivity can be measured by cutting the samples into cubes of *c.* 4 cm side and measuring the resistance between two copper plates. Measurements are usually taken using a sinusoidal

Table 2. *Summary of sites studied*

No.	Location	Site	Soil type	Technique	References for sites
1	Østfold	Onsøy	Very soft to soft clay	ERT	Lunne *et al.* (2003), Berre (2014), Bazin *et al.* (2016)
2	Akershus	Kløfta (BH2284); Kløfta (BH3043)	Soft (quick) clay	ERT and AEM, RCPTU	Anschütz *et al.* (2015, 2017), Christensen *et al.* (2015), Pfaffhuber *et al.* (2016)
3		E16 Sandvika (BH1306)	Soft clay	RCPTU	Rømoen *et al.* (2010)
4		Dobbelspor Skøyen-Asker	Soft (quick) silty clay	ERT	NGI files (e.g. NGI 990032-1) and APEX files
5		RVII Hilleren	Soft to firm clay	ERT	Long *et al.* (2009), Hagberg *et al.* (2007)
6	Buskerud-Drammen	Museumpark	Soft clay	ERT	Bjerrum (1967), Lunne & Lacasse (1999) and APEX files
7		Smørgrav	Soft (quick) clay	ERT, RCPTU, lab	Donohue *et al.* (2009, 2012), Pfaffhuber *et al.* (2010)
8		Vålen	Soft clay	ERT, RCPTU, lab	Rømoen *et al.* (2010), Sauvin *et al.* (2011)
9		Hvittingfoss		ERT and RCPTU	Sauvin *et al.* (2013*a*, 2014)
10	Vestfold	Månejordet	Soft silty clay (quick)	ERT	Statens vegvesen and APEX files
11	Telemark	Skienselven	Soft silty clay (quick)	ERT	NGI files (e.g. 20011544-1, Feb. 2003), Scandiaconsult files (e.g. 620207A, Oct. 2002) and APEX files
12	Sør Trøndelag and Trondheim clay sites	Tiller	Soft to firm (quick) clay	ERT and RCPTU	Sandven (1990), Sandven *et al.* (2004), Gylland *et al.* (2013), Puakowski (2015)
13		Esp	Soft to firm (quick?) clay	ERT and RCPTU	King (2013), Montafia (2013), Hundal (2014), Knutsen (2014), Solberg *et al.* (2016)
14		Klett (South)	Soft silty (quick) clay	ERT and RCPTU	APEX, Multiconsult and NGI files
15		Klett (North)	Soft silty (quick) clay	ERT and RCPTU	Amundsen *et al.* (2015*a*, *b*), APEX and Multiconsult files
16		Dragvoll	Very soft quick clay	ERT and RCPTU	Montafia (2013), Helle *et al.* (2015, 2016), Bazin *et al.* (2016)
17		Leire	Soft silty clay (quick)	RCPTU	Montafia (2013)
18		Rissa (Rein kirke)	Soft and quick clay	ERT and RCPTU	Aasland (2010), Kåsin (2010), Kornbrekke (2012), Sauvin *et al.* (2013*b*)
19		Nidarvoll	Soft (quick) clay	ERT and RCPTU	Hundal (2014), APEX files
20		Melhus, Fallan	Soft (quick) clay	ERT and RCPTU	Sandven *et al.* (2013), Multiconsult and NGU files
21		Melhus, Kaldvelladalen	Soft (quick) clay	ERT	Multiconsult and NGU files
22		Buvika	Soft (quick) clay	ERT	Helle (2004), Solberg *et al.* (2008)
23		Rødde	Soft to firm (quick) silty clay	ERT and RCPTU	Ottesen (2009), Solberg *et al.* (2012)
24	Nord Trøndelag	Levanger, Rinnan	Soft to firm clay	ERT and RCPTU	Pfaffhuber *et al.* (2016), NGI files
25		Levanger, Fleskhus	Soft to firm (quick) clay	ERT and RCPTU	As above
26		Levanger, Hove	Soft to firm clay	ERT and RCPTU	As above
27		Grong	Soft to firm (quick) clay	ERT and RCPTU	Bazin & Pfaffhuber (2013)
28		Kattmarka–Gullvika	Soft to firm (quick) clay	ERT	Nordal *et al.* (2009), Johansson *et al.* (2013), NGU, Multiconsult and NGI files
29		Kattmarka	Soft to firm (quick) clay	ERT	As above
30	Nordland	Finneidfjord	Soft silty–sandy clay	ERT	Longva *et al.* (2003), Lecomte *et al.* (2008*a*,*b*), L'Heureux *et al.* (2011)

Table 3. *Summary of soil properties at study sites*

	Site	w (%)	ρ (Mg m^{-3})	Clay (%)	I_p (%)	S_t	OCR	V_s (m s^{-})	Resistivity (Ω m)
1	Onsøy	60 – 65	1.635	40 – 60	33 – 40	4.5 – 6	1.5 – 1.3	80 – 140	1 – 36
2	Kløfta (BH2284)	28 – 45	1.71 – 2.00		12 – 19	1 – 90			3 – 51
	Kløfta (BH3043)	32 – 49	1.78 – 1.87		15 – 22	5 – 73			
3	E16 Sandvika (BH1306)	38 – 50	1.69 – 1.94		9 – 17	8 – 26			21 – 37
4	Dobbeltspor Skøyen-Asker	22 – 40	1.8 – 2.1		3	10 – 200		110 – 180	20 – 49
5	RVII Hilleren	30 – 40	1.82 – 1.89	28 – 45	8 – 18	7 – 135	1.2 – 2.6	170 – 200	21 – 76
6	Museumpark	50 – 55	1.72 – 1.78	48	30	7 – 8	1.5	100 – 170	4 – 37
7	Smørgrav	35 – 45	1.80 – 1.93	36 – 60	9 – 22	5 – 77		105 – 230	3 – 62
8	Vålen	35 – 47	1.85 – 2.01	37 – 39	15 – 22	5 – 15	1.2 – 1.8	100 – 240	3 – 65
9	Hvittingfoss	22 – 36	1.91 – 2.09	17 – 36	4 – 6	>100		150 – 250	33 – 95
10	Månejordet								
	2.5 – 5.5	28 – 50	1.83 – 2.09	20	14 – 16	<10	4.5 – 5.5	110 – 180	35 – 165
	5.5 – 14.5	25 – 40	1.83 – 2.00	24 – 27	6 – 9	50 – 350			
11	Skienselven	26 – 33	1.95 – 2.0		3	110 – 240		86 – 150	63 – 169
12	Tiller	30 – 45	1.8 – 2.0	35 – 40	2 – 8	5 – 1000	2 – 4	75 – 230	29 – 102
13	Esp	30 – 50	1.75 – 1.95	30 – 40	3 – 15	10 – 115	2 – 4	100 – 220	6 – 192
14	Klett (South)	22 – 36	1.92 – 2.04	28 – 35	2 – 10	10 – 240	1.5 – 3	120 – 250	4 – 108
15	Klett (North)	30 – 40	1.92 – 2.04	27 – 36	6 – 10	10 – 300	1.2 – 2.4		4 – 52
16	Dragvoll	30 – 42	1.88 – 2.0	28 – 48	4 – 12	16 – 152	1 – 2	110 – 190	34 – 113
17	Leire	25 – 29		31 – 38	5 – 7	5 – 115			24 – 102
18	Rissa (Rein kirke)	28 – 40	1.85 – 2.0	42 – 47	7 – 12	10 – 60	2 – 4	100 – 280	4 – 170
19	Nidarvoll	25 – 45	1.78 – 2.04		1 – 20	5 – 200+			32 – 80
20	Melhus, Fallan	30 – 37	1.88 – 1.97	32 – 34	3 – 12	10 – 144	3–?		15 – 68
21	Melhus, Kaldvelladalen	28 – 42	1.92 – 1.97	35	7 – 12	6 – 144			2 – 100
22	Buvika	30 – 39	1.87 – 1.97	28 – 47	12 – 17	15 – 250+			7 – 66
23	Rødde	26 – 33	1.95 – 2.01	30 – 47		3 – 235			2 – 107
24	Levanger, Rinnan	25 – 32	1.99 – 2.04	42	5	5 – 40			31 – 88
25	Levanger, Fleskhus	21 – 31	1.89 – 2.04	50	10	8 – 100			30 – 188
26	Levanger, Hove	20 – 30	1.94 – 1.98	50	10	2 – 20			11 – 92
27	Grong	26 – 33	1.98 – 2.12		6 – 13	3 – 510			41 – 129
28	Kattmarka–Gullvika	28 – 38	1.92 – 2.01	24 – 35	6 – 9	4 – 67			11 – 66
29	Kattmarka	29 – 36	1.91 – 2.04	42 – 44	8 – 12	7 – 35	1.45 – 7.0	105 – 190	5 – 27
30	Finneidfjord	28 – 40	1.86 – 2.09	9 – 17		3 – 11			37 – 212

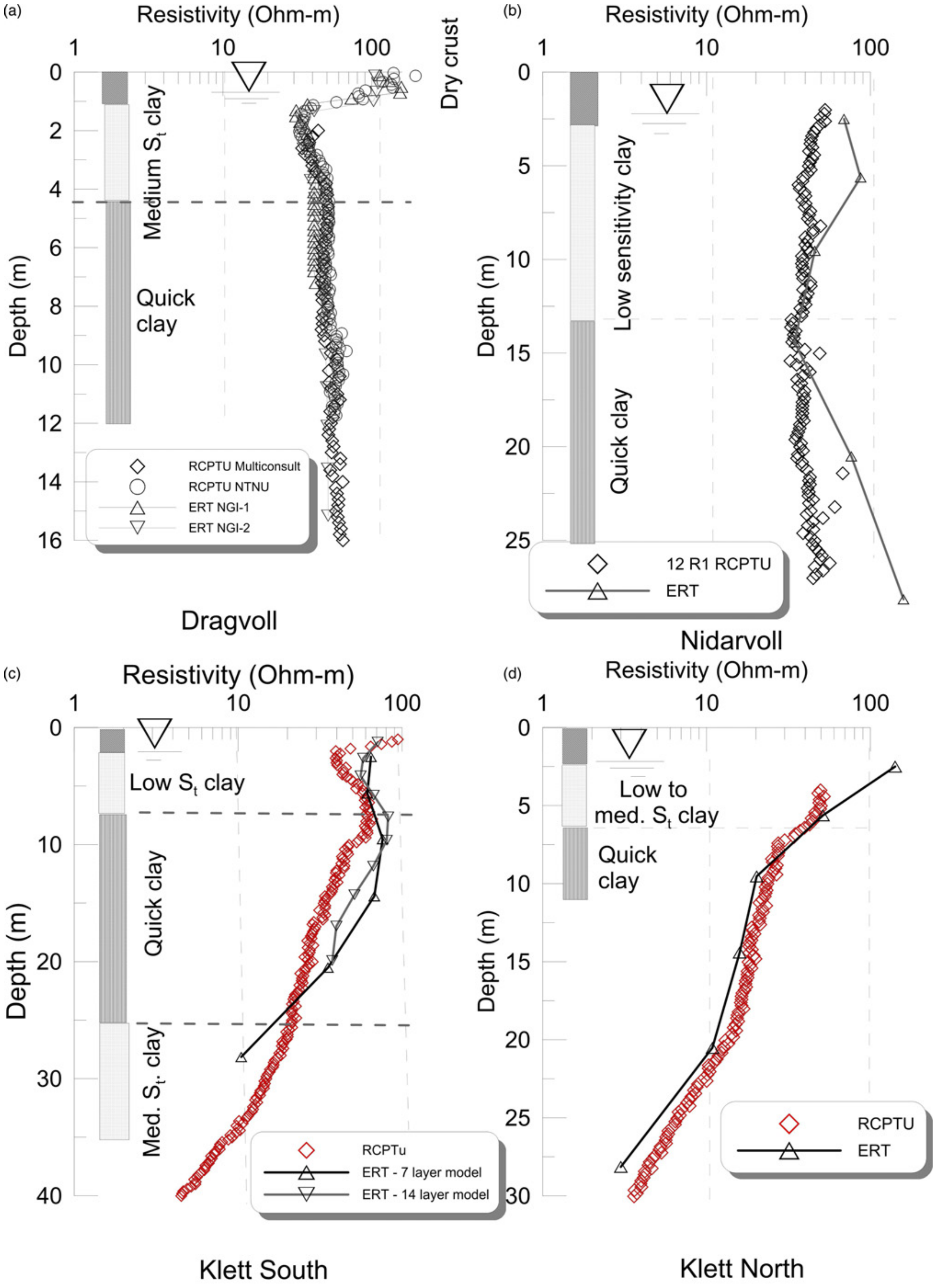

Fig. 5. Resistivity measurements for sites in Trondheim area: (**a**) Dragvoll; (**b**) Nidarvoll; (**c**) Klett South; (**d**) Klett North.

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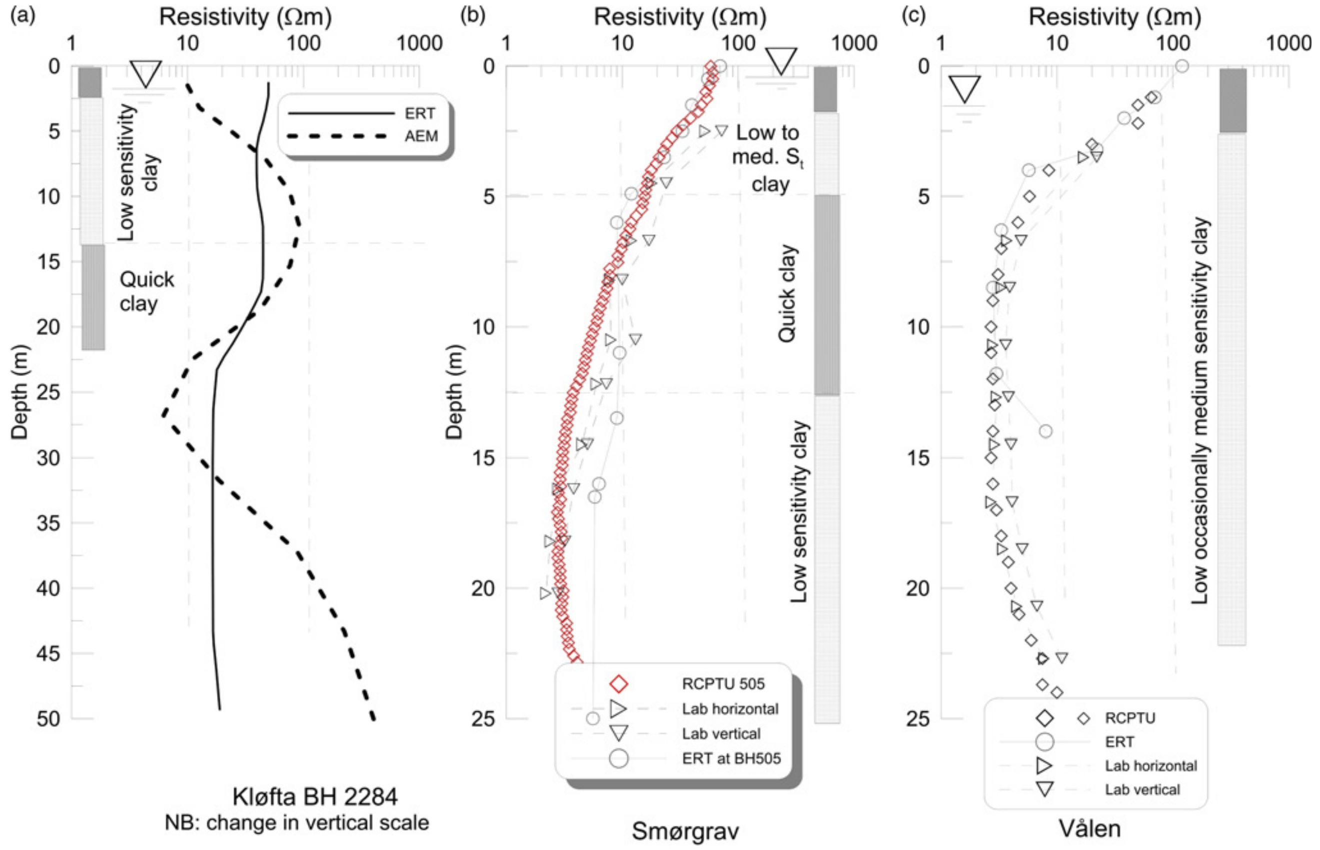

Fig. 6. Resistivity measurements for sites in South East Norway: (**a**) Kløfta BH 2284; (**b**) Smørgrav; (c) Vålen.

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current at a frequency of 1 kHz. Single-axis sample resistivity measurements are typically done in a test tube containing a similar setup to those for RCPTU or ERT measurements with two current and two potential electrodes. Alternatively, triaxial or odometer cells can be modified to measure resistivity using metallic discs as electrodes (Gribben *et al*. 2016). These configurations allow the sample to be reinstated to its original state and also a more stable electrode–soil contact than the free-air test described above. Laboratory tests should be undertaken shortly after sampling as chemical reactions within the samples can have an effect on the measured resistivity.

Scale differences

Laboratory measurements are arguably the most accurate data as long as one bears in mind that the sample quality determines the applicability of the resistivity readings. RCPTU readings are small-scale compared with ERT or AEM readings. No inversion is required during the data acquisition and therefore the measurement resolution is constant throughout the RCPTU profile. However, RCPTU probes require regular calibration. Proximity to bedrock or other resistive bodies off-line can bias the ERT and AEM soundings. When comparing resistivity measurements, it is important to be aware that these are influenced by a soil volume involving some centimetres (laboratory) to some tens of centimetres for RCPTU, some metres to tens of metres for ERT, and finally some tens of metres to some hundreds of metres for AEM. Bearing all these factors in mind, all three methods derive consistent and overlapping information (see Figs 2, 3, 5 and 6, and Pfaffhuber *et al*. 2016).

Geotechnical soil sampling and testing

In Norway standard site investigation procedure is to recover continuous piston samples of unconsolidated overburden 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 sampler (Andresen & Kolstad 1979), working either as a thin-walled steel piston sampler or as a composite piston sampler using plastic inner tubes. 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 porewater in a centrifuge and using a correlation between measured electrical conductivity (inverse of resistivity) 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 (1946) calibration with some local modifications and additions.

Resistivity results

Comparison of results, Central Norway

Some resistivity results for the Tiller site are shown in Figure 2d and data for four other sites in Central Norway are shown in Figure 5. Resistivity data were measured using either ERT or RCPTU techniques as well as by both methods at some sites. Despite being in layers of sensitivity varying from low sensitivity ($S_t < 8$) to quick, many of the data fall in the range 10 –100 Ω m, corresponding to leached clay according to Solberg *et al.* (2012). Resistivity clearly decreases with depth for three of the five sites, with only the

Dragvoll data showing a distinct increase with depth. Data from the two resistivity probes, those of Multiconsult and NTNU, give the same result. Two sets of ERT measurements were made at Dragvoll at different times and these give very similar output. For Klett South ERT data were selected from two resistivity models and both give similar results. ERT and RCPTU data compare very well, showing very similar values and the same pattern with depth. The fit between the two sets of data is excellent for the Dragvoll and Klett North sites, but is not as good for Tiller, as the ERT line was located some 20 m from the RCPTU probes, or for the Nidarvoll site, as these ERT data were not acquired with the necessary resolution.

Comparison of results, South East Norway

Similar data for three sites in South East Norway are shown in Figure 6. Figure 6a compares resistivity values obtained by AEM with those obtained by ERT for the E16 site near Kløfta. Some further similar examples for this site have been given by Pfaffhuber *et al.* (2016) and Anschütz *et al.* (2017). ERT and AEM models were shown to agree well both in the values of the resistivity measured and in the pattern of the resistivity profile with depth. Vertical variation in the resistivity distribution appears to be overestimated in the AEM method compared with the ERT method. This is a result or bias of the inversion algorithm used. Solberg *et al.* (2016) made similar findings for a quick clay area at Esp near Trondheim.

RCPTU, ERT and laboratory resistivity measurements for the Smørgrav and Vålen sites are shown in Figure 6b and c respectively. The laboratory measurements were carried out using the ‘free air’ method described above. These two sites are distinctly different, with that at Smørgrav having a layer of quick clay between two layers of low- to medium-sensitive clay and Vålen having low- to medium-sensitive clay only, with no quick clay present. All three techniques give similar values, with a difference no bigger than 5 Ωm, and show the same trend with depth. The laboratory measurements also show that the clays at both sites show some anisotropy of resistivity, with the horizontal values being slightly Q4 lower than the vertical ones. Smørgrav is possibly the only site investigated to date where the low-sensitivity layer underlying the quick clay is thick enough that the resistivity measurements can be interpreted as a representative stable value for unleached, saline clay.

Summary of all RCPTU data

A summary of all the measured resistivity values is given in Table 3. Quick clay data from both regions are characterized by the following consistent key features.

(1) Changes in resistivity are generally gradual with depth; no sharp interfaces are evident in any of the methods used. This corresponds to observed gradual changes in soil salinity.

(2) Data points with relatively high resistivity (typical for quick clay) but low sensitivity appear generally in shallow layers as quick clay overburden.

(3) Of the 30 sites studied, 24 show a decrease in resistivity with depth, suggesting that many of the sites have been leached or weathered near the surface.

(4) Resistivity estimates based on the various geophysical methods are generally consistent within their respective resolution limits.

(5) The definition of quick or non-quick clay is based on one to two geotechnical parameters (c_{ur} and S_{t}). Based on resistivity alone, no such definition can be made given all the uncertainties and equivalences mentioned above. ‘High’ resistivity may indicate quick clay but also ‘over-leached’ clay. On the other hand, ‘low’ resistivity very probably indicates unleached, non-sensitive clay (see, e.g. Fig. 2).

Further to these rather qualitative conclusions, the question remains as to whether any quantitative relationships may be established. The following investigates this matter in detail.

Link with geotechnical parameters

Theoretical and empirical models

The electrical conductivity or resistivity of sediments and rocks is primarily governed by the conductivity of the pore space, as most matrix minerals are highly resistive, with the exception of some ore minerals. Studies aiming at developing petrophysical models that relate resistivity to porosity and salinity date back to the early 20th century. In fact, resistivity sounding and logging was one of the first geophysical methods applied in hydrocarbon exploration and was used to test whether sandstone formations were saturated with brine or oil. The most famous and still most commonly used model, that of Archie (1942), was developed for this application and is based on empirical factors from laboratory tests on sandstone cores that relate bulk conductivity to the liquid phase assuming a non-conductive matrix.

Materials that contain both sand and clay particles extend the simple Archie model, as parts of the matrix also contribute to the bulk conductivity. Numerous studies have attempted to describe, discretize and model the very complex mechanisms that govern electrical conductivity of clay–sand–brine mixtures. Quoting Doveton (2001), none of these models are correct but some are useful. Attempts have been made to extend Archie’s model to account for clay particles in the pore space of sandstones (Doveton 2001). Most of these attempts are not useful for clay soils, as they generally assume a small clay content that is limited to the sand porosity. Glover *et al.* (2000) extended Archie’s formulation to a two-phase conductivity model with both pore space and matrix assumed to be conductors. Konishi (2015) suggested a three-phase model consisting of porewater, porous clay and sand, in an attempt to account for the capillary conductivity in the small clay pores. Similar attempts have been made by soil scientists; for example, by Rhoades *et al.* (1976), accounting for the liquid phase and clay surface conductivity.

Probably the most relevant model for Norwegian clays has been presented by Shevnin *et al.* (2007) and accounts for both ion conductivity and electric-double-layer conductivity in the pores of clay and sand, connected electrically both in parallel and in series. The very complex pore conductivity model integrates capillary conductivity depending on pore radii and variable double-layer thickness. Two types of equations are used for clay contents higher and lower than sand porosity, distinguishing sand–silt with clay ‘smeared out’ in the sand porosity and sandy clay with sand grains ‘floating’ in a clay matrix, respectively.

Salt content of the pore fluid

The relationship between resistivity and salt content (S) of the pore fluid is shown in Figure 7a. This figure represents an extension of that given by Long *et al.* (2012), with data for an extra nine sites having been added here. As expected, the link between these two parameters is strong. Resistivity decreases rapidly with increasing salt content. The exponential trendline shows a relatively good coefficient of correlation (R^2) value of 0.81. Studying the relationship on a linear scale may lead one to see large scatter in the measured resistivity values for low salt content and almost constant resistivity for high salinities. Use of double logarithmic scales (Fig. 7b) clearly shows the direct correlation between salinity

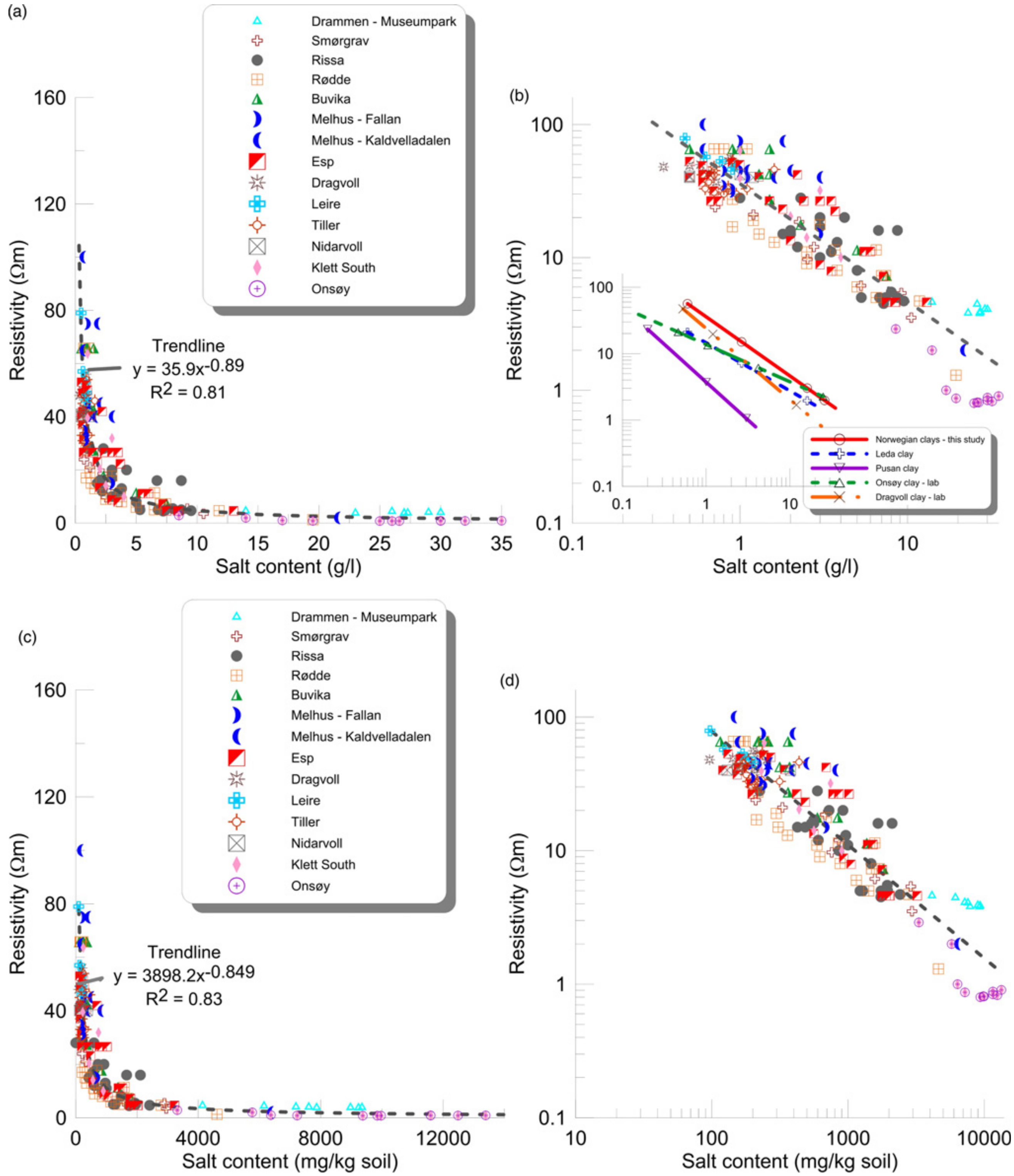

Fig. 7. Resistivity v. salt content (**a**) natural scale in g l^{-1}; (**b**) log scale in g l^{-1}; (**c**) natural scale in mg kg^{-1}; (**d**) log scale in mg kg^{-1}; (**e**) with data grouped in water content ranges; (**f**) with data grouped in clay content ranges. ; (**c**) and (**d**) Resagainstsaltinggperkg.grf; (**e**) and (**f**) resagainstsaltloglogClayandWIntervals.grf.)

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and resistivity over several orders of magnitude, consistent with the petrophysical models discussed above.

No significant change in correlation was observed when resistivity was related to the salt concentration per unit volume of soil (S' expressed in mg kg^{-1} of soil; see Fig. 7c and d). Assuming the density of water is 1000 kg m^{-3},

$$S' = S\frac{w}{1+w}. \tag{1}$$

One would expect a somewhat improved relationship here, as S' accounts for the influence of porosity and water content. However, the difference is only marginal owing to the limited range of water content values measured, although a slightly higher R^2 value of 0.83 is obtained.

Øveraas (2016) described a series of experiments in which water with varying salt content was diffused through cylindrical samples of Dragvoll clay from Trondheim. Resistivity values were measured via electrodes protruding into the samples. Similarly, Gribben *et al*. (2016)

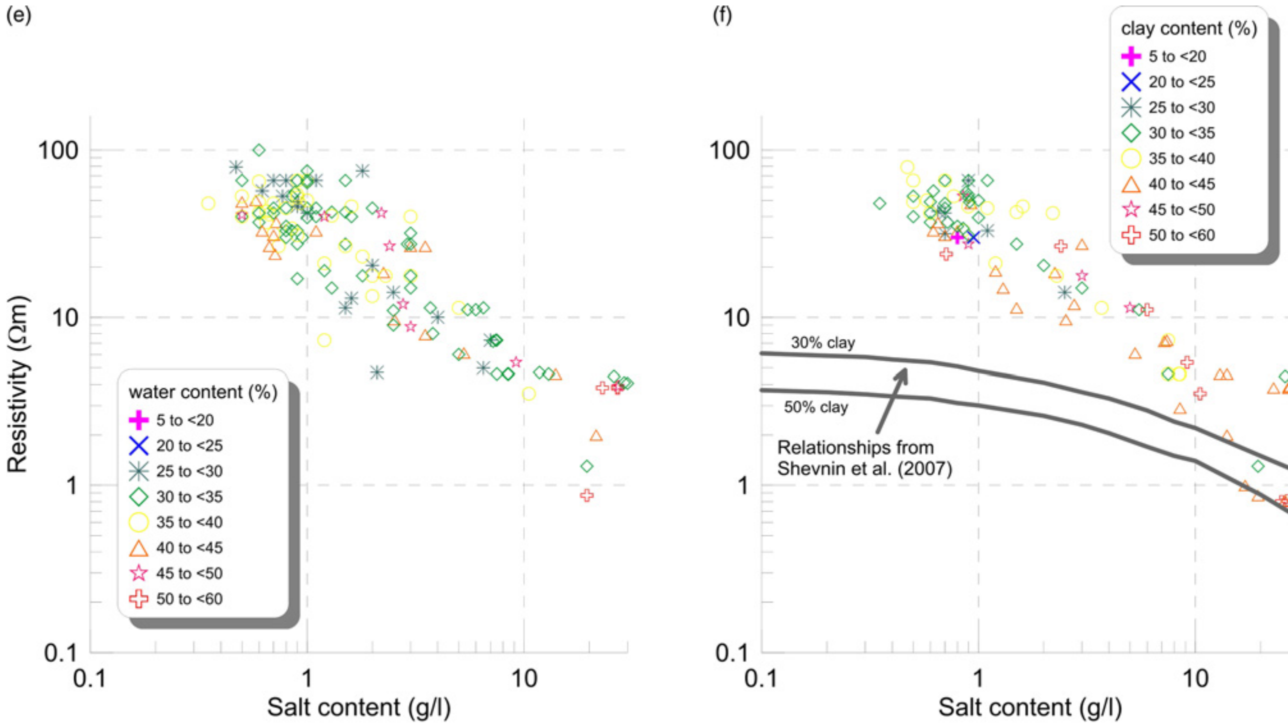

Fig. 7. Continued.

described some similar laboratory experiments on Onsøy clay in which the initial high salt content was gradually leached. Relationships between resistivity and porewater salt content for both of these trials are shown in the inset to Figure 7b and can be seen to follow the same pattern with comparable numerical values to those for the general body of Norwegian clays from this study.

An empirical relationship between porewater salt content and electromagnetic conductivity (EM-39) has previously been developed for Canadian Champlain Sea sediments by Hyde & Hunter (1998) and Calvert & Hyde (2002). Those researchers found that

$$S = 0.4663 + 0.0002985C^{1.752} \pm 1.31 \qquad (2)$$

where C is the conductivity (in mS m^{-1}).

If conductivity is converted to resistivity, this relationship shows a very similar trend to that found here, with the relationship for the Norwegian clays giving a higher resistivity for a given salt content (see Fig. 7b).

Giao *et al.* (2003) also determined the relationship between resistivity and salt content for Pusan clay from South Korea. Salt content varied between 0.2 and 3.9 g l^{-1}. A similar relationship to that for the Norwegian clays was found but the trendline for the Pusan data falls below that of Norwegian clays.

Porosity–water content

All of the soils studied here can be considered fully saturated. Also, they have very similar specific gravity values in the range 2.6 – 2.75.

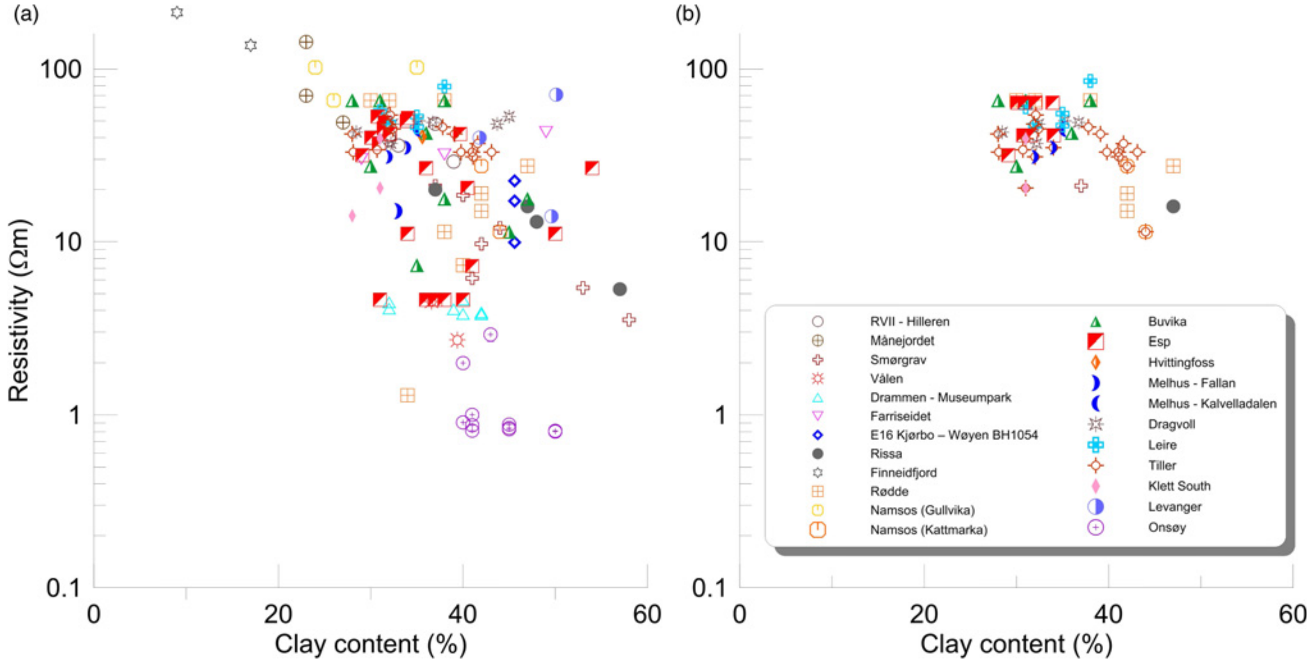

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Fig. 8. Resistivity v. clay content: (**a**) all available data; (**b**) data with salt content less than 2 g l^{-1} only.

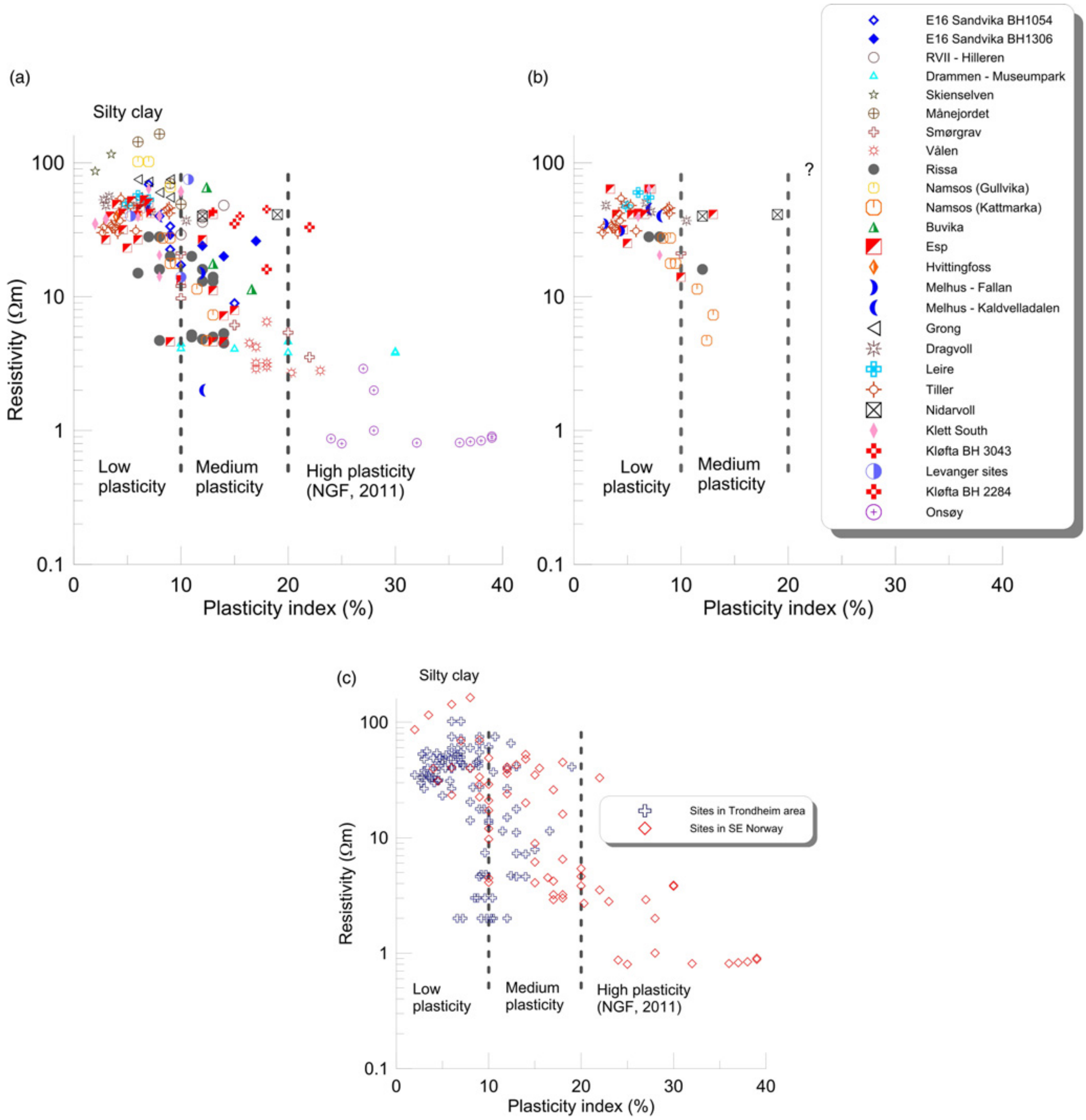

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Fig. 9. Resistivity v. plasticity index: (**a**) all available data; (**b**) data with salt content less than 2 g l^{-1}; (**c**) sites in the Central Norway area and in South East Norway.

Therefore any relationship between resistivity and water content will be similar to that between resistivity and porosity. Here the range of water content values is relatively narrow, being mostly between 25 and 45%. In Figure 7e resistivity is plotted against salt content, with the data being subdivided into groups corresponding to different water content ranges. No clear relationship can be observed, as the salt content is the determining factor.

Clay content

The relationship between resistivity and clay content, for all the available data, is shown in Figure 8a. Most of the samples lay between 35 and 40% clay content. There is some relationship 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. However, this seems to have only a small influence. A change from 35 to 40% clay content may change the resistivity by 10%, whereas a change from 2 to 7 g l^{-1} salt content may decrease resistivity by 50% (Fig. 7a and b). Only at low salt content does the clay content play a more dominant role. This is somewhat evident in Figure 8b, which focuses only on the data where salt content is less than 2 g l^{-1}. Only at very low clay content (<20%) does resistivity drastically increase towards values typical for silt–sand.

Some of the theoretical curves developed by Shevnin *et al.* (2007) are superimposed on the data gathered for this project in Figure 7f. Although the data presented here clearly mirror the theoretical trend with respect to salinity, there is no clear dependence on clay content. The Shevnin *et al.* (2007) relationships do not match the measured data, probably owing to the fundamentally different

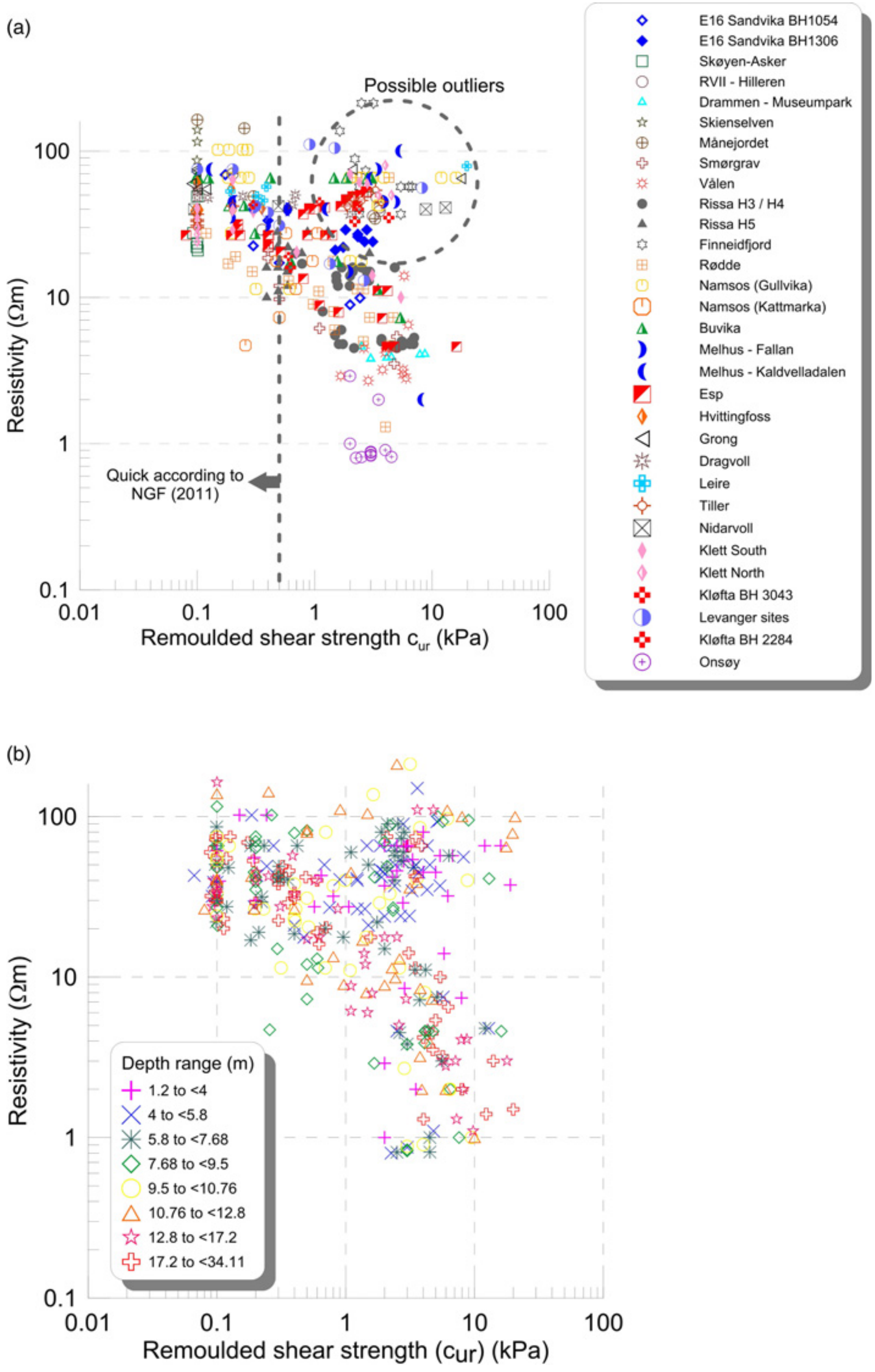

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Fig. 10. Resistivity v. remoulded shear strength: (**a**) all data; (**b**) plotted with respect to depth zones.

sand and clay porosities, both in the numerical values involved and in the nature of the pore space in these two contrasting soil types. However, they do illustrate the relatively minor influence of clay content, within the range applicable here (30 – 50%), relative to the dominant influence of salt content.

For clay content greater than sand porosity the Shevnin *et al.* (2007) model can be simplified to

$$\sigma = \sigma_{cc} C_c \Phi_c \tag{3}$$

with σ, σ_{cc}, C_c and Φ_c being the bulk conductivity, clay capillary conductivity, clay content and clay porosity, respectively.

Using equation (3), attempts were made to normalize all measured bulk resistivity to one common clay content (i.e. 35%, which was the average clay content for the dataset) in an attempt to remove the clay dependence from the data. In this way, samples with clay content higher than 35% should have a reduced normalized conductivity and vice versa. However, these normalized data did not indicate a systematic change or improvement. This observation needs to be seen in the context of the discussion on the usefulness of such models, described above, when dealing with a variable, large dataset rather than data from controlled laboratory studies. It should be noted that, common for all of the models discussed above, at a constant porosity and saturation, bulk conductivity correlates linearly with the porewater conductivity, limited to a certain range of porewater salinity.

Plasticity index

A similar pattern to that of clay content emerges in the plot of resistivity against I_p in Figure 9a. Again, there is some trend of reducing resistivity owing to increasing I_p, which is arguably stronger than that for clay content. However, I_p in sensitive clays varies not only with the grain size and clay content of the soil but also with the intensity of the leaching. For example, Bjerrum (1954) showed that, for clay sites in the Oslo area, natural leaching of the material by freshwater resulted in a drop in liquid limit (w_L) from 45 to 25%, whereas the plastic limit (w_P) shows a much lower reduction from about 20 to 17%. Similarly, Helle *et al.* (2016, 2017*a*) showed that w_L and w_P of the clays at Dragvoll and Ulvensplitten both increased by similar amounts to the Oslo clays when they were treated with potassium chloride via salt wells. Hence the sensitive clays may show a relatively lower I_p than similar non-sensitive 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 (NGF 2011), the resistivity values are low and decrease from about 5 Ω m at an I_p of 20% to 1 Ω m at an I_p of 40%. All of the values with I_p greater than 20% correspond to samples in which the salt content exceeds 8 g l^{-1} (see also Fig. 7). For the medium- and low-plasticity materials the resistivity values are generally higher but are more scattered, probably for the reasons discussed above. In Figure 9b those data with salt content less than 2 g l^{-1} only are shown, and here the pattern of decreasing resistivity with increasing I_p for the low- to medium-plasticity clays is somewhat clearer.

It is also important to study the possible influence of mineralogy on the resistivity values, and in Figure 9c those data from the Central Norway area and from South East Norway are plotted separately. Although, in general, the data from South East Norway show higher I_p values there is no clear pattern in the data. This finding is consistent with that of Syversen (2013), who studied the mineralogy and index properties of 102 samples of clays from all over Norway and found the mineralogy to be relatively uniform with no clear trends in the data.

Resistivity and remoulded shear strength

Norwegian marine clays are considered quick if c_{ur} is less than or equal to 0.5 kPa and thus any possible relationship between c_{ur} and resistivity is of significant interest. As seen in Figure 10a there is a clear trend of decreasing resistivity with increasing c_{ur}, as would be expected given that c_{ur} will decrease with increasing intensity of leaching and thus decreased salinity. However, there is considerable scatter in the data and there appears to be a patch of inconsistent data that shows high resistivity and high c_{ur}. Based on resistivity measurements only, these data would falsely be interpreted as quick clay (false positives) even though they fall within the range 10 – 100 Ω m, often considered as typical for quick clay (Solberg *et al.* 2012). It should be noted, however, that no outliers are observed that would lead to false negatives. In other words, low resistivity (<10 Ω m) always relates to high remoulded shear strength (>0.5 kPa).

In Figure 10b the same data are plotted with respect to depth zones. It can be seen that many of the data in the outlier area correspond to those shallower than 7.68 m; that is, data in the dry crust or those corresponding to relatively deep weathering. This is probably due to the long-term ion exchange pattern and geochemistry of the material as discussed above. There are also some further points in this outlier zone corresponding to silty material.

Trends for deeper and non-silty material

The plots of resistivity v. plasticity index (Fig. 9a) and resistivity v. remoulded shear strength (Fig. 10a) have been reproduced in Figure 11 with all data from depths greater than 7.5 m and data for the silty materials at Månejordet, Finneidfjord and Gullvika removed. In this case the pattern of decreasing resistivity with increasing plasticity index and c_{ur} is much clearer. Potential correlations between resistivity and remoulded shear strength vary significantly depending on whether shallow data are included or not. Interestingly, weathering appears to have less effect on the resistivity–plasticity correlation than on the resistivity–remoulded shear strength, with shallow data agreeing with deeper data for the former dataset.

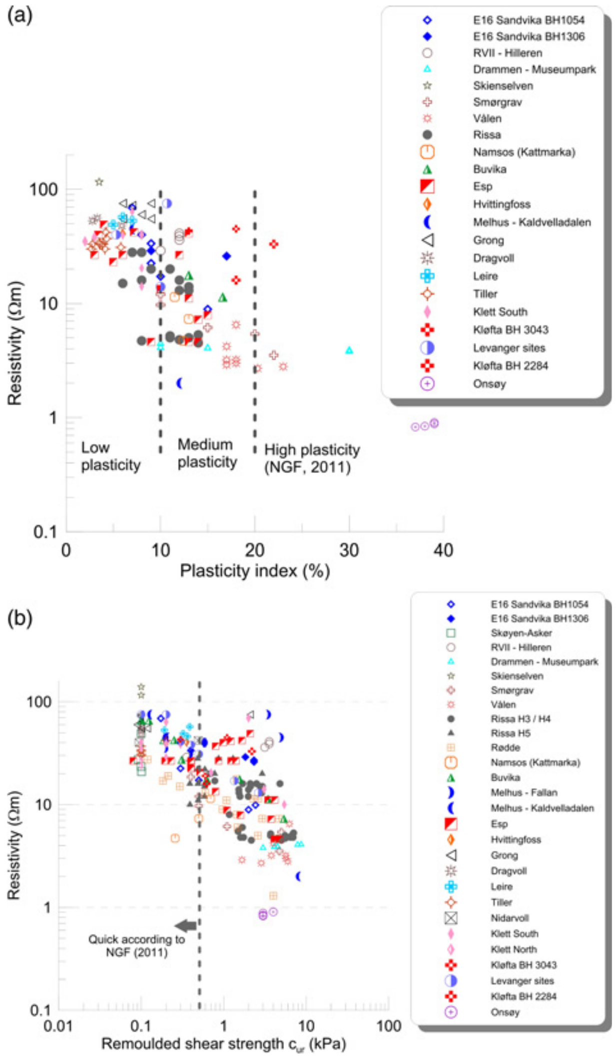

Fig. 11. Resistivity data from depths less than 7.5 m and silty data removed v. (**a**) plasticity index and (**b**) remoulded shear strength.

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Combining the data in Figure 11a and b it would seem that if the resistivity is between 10 and 100 Ω m and $I_p > 10\%$, then it is less likely that the material is a sensitive or quick clay.

Summary and conclusions

The main objectives of this work were to study the reliability and repeatability of the methods used to measure resistivity in Norwegian marine clays, to examine the data obtained and to assess their usefulness in characterizing the materials, particularly for quick clays. It was also hoped to identify the material properties that control the measured resistivity values. Of particular interest was the study of materials that have been leached but are not quick. The objectives were achieved by analysing data from 30 Norwegian sites. The following features were found.

(1) Resistivity measurements are consistent whether acquired in boreholes, on the surface or from the air within the scale overlap of

the different methods. Sampling volumes range from hundreds of square centimetres to hundreds of square metres.

(2) For Norwegian glacio-marine clay resistivity is primarily defined by the porewater salt content–conductivity, with minor additional influence by clay content and porosity as the latter two vary insignificantly.

(3) Clay content influences resistivity only in low salt content (<2 g l^{-1}) samples.

(4) There is no geographical difference in the resistivity values, which are similar and follow the same patterns throughout Norway. This is consistent with the relatively uniform clay mineralogy throughout the country.

(5) Indirectly, resistivity clearly correlates with remoulded shear strength, the determining factor to identify quick clay, and the plasticity index.

(6) The resistivity–c_{ur} correlation is limited to samples that are deeper than the dry crust and deep weathering zone, found to be around 7.5 m. In these shallower depths extended chemical weathering re-stabilizes the leached clay, leading to potential false negatives, where resistivity data alone may indicate quick clay.

(7) Whereas high resistivity (>10 Ω m) may indicate quick or weathered clay, low resistivity (<10 Ω m) conclusively points to stable, unleached clay in all studied samples.

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References

Aasland, R. 2010. *Kartlegging av kvikkleire med 2D resistivitet og RCPT i Rissa*. MSc thesis, Norwegian University of Science and Technology (NTNU), Trondheim.

Amundsen, H.A., Emdal, A., Sandven, R. & Thakur, V. 2015*a*. On engineering characterisation of a low plasticity sensitive clay. *In*: *GEOQuébec 2015 – Challenges from North to South, Québec, Canada*. Q5

Amundsen, H.A., Thakur, V. & Emdal, A. 2015*b*. Comparison of two sample quality assessment methods applied to oedometer test results. *In*: Rinaldi, V.A. (ed.) *6th International Symposium on Deformation Characteristics of Geomaterials*. IOS Press, Amsterdam, 923–930.

Andresen, A. & Kolstad, P. 1979. The NGI 54 mm samplers for undisturbed sampling of clays and representative sampling of coarser materials. *In*: *Proceedings International Symposium on Soil Sampling, Singapore*, 13–21. Q6

Anschütz, H., Bazin, S. & A., P. 2015. Towards using AEM for sensitive clay mapping – A case study from Norway. *In*: *First European Airborne Electromagnetics Conference/Near Surface Geoscience, EAGE, Turin*, Extended abstract, MO AEM 04, 05. Q7

Anschütz, H., Bazin, S., Kåsin, K., A.A., P. & Smaavik, T.F. 2017. Airborne sensitive clay mapping - stretching the limits of AEM resolution and accuracy. *Near Surface Geophysics*, https:doi.org/10.3997/1873-0604.201701 Q8

Appelo, C. & Postma, D. 2005. *Geochemistry, Groundwater and Pollution*. Balkema, Leiden.

Archie, G.E. 1942. Electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of the American Institute of Mining and Metallurgical Engineers*, **146**, 54–62.

Aylsworth, J.M. & Hunter, J.A. 2004. A geophysical investigation of the geological controls on landsliding and soft deformation in sensitive marine clay near Ottawa. *In*: *57th Canadian Geotechnical Conference, Géo Québec*, 30–37. Q9

Bazin, S. & Pfaffhuber, A.A. 2013. Mapping of quick clay by electrical resistiivty tomography under structural constraint. *Journal of Applied Geophysics*, **98**, 280–287, https://10.1016/j.jappgeo.2013.09.002

Bazin, S., Gribben, S., Eide-Helle, T., Sauvin, G., Anschütz, H., Pasquet, S. & Donohue, S. 2016. Geophysical characterisation of clay sites: field and lab tests. *In*: *5th International Conference on Geotechnical and Geophysical Site Characterisation (ISC'5), Gold Coast, Australia*. Q10

Berre, T. 2014. Test fill on soft plastic marine clay at Onsøy, Norway. *Canadian Geotechnical Journal*, **51**, 30–50.

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

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

Calvert, H.T. & Hyde, C.S.B. 2002. Assessing landslide hazards in the Ottawa Valley using electrical and electromagnetic methods. *In*: *Proceedings, Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP'02), Las Vegas*, 11. Q11

Christensen, C.W., Pfaffhuber, A.A., Anschütz, H. & Smaavik, T.F. 2015. Combining airborne electromagnetic and geotechnical data for automated depth to bedrock tracking. *Journal of Applied Geophysics*, **119**, 178–191.

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

Dahlin, T., Löfroth, H., Schälin, D. & Suer, P. 2013. Mapping of quick clay using geoelectrical imaging and CPTU resistivity. *Journal of Near Surface Geophysics, EAGE*, **11**, 659–670, https://doi.org/10.3997/1873-0604.2013044

Donohue, S., Long, M., O'Connor, P., Eide-Helle, T., Pfaffhuber, A.A. & Rømoen, M. 2009. Assessment of geophysical techniques for the mapping of quick clay deposits in Norway. *In*: *Proceedings Near Surface 2009 – 15th European Meeting of Environmental and Engineering Geophysics, September, Dublin*, Paper C17. Q12

Donohue, S., Long, M., O'Connor, P., Eide-Helle, T., Pffaffhuber, A.A. & Rømoen, M. 2012. Geophysical mapping of quick clay: a case study from Smørgrav, Norway. *Journal of Near Surface Geophysics, EAGE*, **10**, 207–219.

Doveton, J.H. 2001. All models are wrong, but some models are useful: 'solving' the Simandoux equation. *In*: *Annual Conference of the International Association of Mathematical Geology, Cancun, Mexico*. Q13

Eggestad, A. & Sem, H. 1976. Stability of excavations improved by salt diffusion from deep wells. *In*: *6th European Conference on Soil Mechanics and Foundation Engineering (ECSMFE), Vienna*, 211–216. Q14

Giao, P.H., Chung, S.G., Kim, D.Y. & Tanaka, H. 2003. Electric imaging and laboratory resistivity testing for geotechnical investigation of Pusan clay deposits. *Journal of Applied Geophysics*, **52**, 157–175, https://doi.org/10.1016/S0926-9851(03)00002-8

Glover, P.W.J., Hole, P.J. & Pous, J. 2000. A modified Archie's law for two conducting phases. *Earth and Planetary Science Letters*, **180**, 369–383.

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

Gribben, S., Donohue, S., Sivakumar, V., Bazin, S., Berre, T. & L'Heureux, J.-S. 2016. Geophysical methods for assessing the geotechnical properties of sensitive clays. *In*: *GeoVancouver 2016, Vancouver, Canada*. Q15

Gylland, A., Long, M., Emdal, A. & Sandven, R. 2013. Characterisation and engineering properties of Tiller clay. *Engineering Geology*, **164**, 86–100, https://doi.org10.1016/j.enggeo.2013.06.008

Hagberg, K., Long, M. & El Hadj, N. 2007. Experience of 54 mm and 75 mm sampling in Norwegian soft clays. *In*: al., C.E. (ed.) *Proceedings 14th European Conference on Soil Mechanics and Geotechnical Engineering (ECSMGE), Madrid*. MillPress, Rotterdam, 1643–1649. Q16

Helle, T.E. 2004. *E39 Vigda, Buvika, Profile 3 – Natural Slope*. MSc thesis, Norwegian University of Science and Technology (NTNU), Trondheim.

Helle, T.E., Bryntesen, R.N., Amundsen, H.A., Emdal, A., Nordal, S. & Aagaard, P. 2015. Laboratory setup to evaluate the improvement of geotechnical properties from potassium chloride saturation of a quick clay from Dragvoll, Norway. *In*: *GEOQuébec 2015 – Challenges from North to South, Québec*. Q17

Helle, T.E., Nordal, S., Aagaard, P. & Lied, O. 2016. Long term effect of potassium chloride treatment on improving the soil behaviour of highly sensitive clay, Ulvensplitten, Norway. *Canadian Geotechnical Journal*, **53**, 410–422.

Helle, T.E., Aagaard, P. & Nordal, S. 2017*a*. *In situ* improvement of highly sensitive clays by potassium chloride migration. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, **143**, https://doi.org/10.1061/(ASCE)GT.1943-5605.0001774

Helle, T.E., Aagaard, P. & Nordal, S. 2017*b*. Improving the post failure properties in quick clay by treatment with potassium chloride. *In*: Thakur, V., L'Heureux, J.-S. & Locat, A. (eds) *International Workshop on Landslides in Sensitive Clays (IWLSC), Trondheim*. Springer, Berlin. Q18

Hundal, E. 2014. *CPTU med målt total sonderingsmotstand, Nye muligheter for å detektere kvikkleire?* Masters thesis, Norwegian University of Science and Technology (NTNU), Trondheim.

Hyde, C.S.B. & Hunter, J.A. 1998. Formation electrical conductivity–porewater salinity relationships in Quaternary sediments from two Canadian sites. *In*: *Symposium on the Application of Geophysics to Environmental and Engineering Applications (SAGEEP '98), Chicago*, 499–510. Q19

Johansson, J., Løvholt, F., Andersen, K.H. & Madshus, C. 2013. Impact of blast vibrations on the release of quick clay slides. *In*: *18th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE), Paris*, 1507–1509. Q20

Kåsin, K. 2010. *CPTU i kvikkleire i Rissa*. Masters thesis, Norwegian University of Science and Technology (NTNU), Trondheim.

King, J. 2013. *Testing of clays at landslide site at Esp, Bynesset*. Masters thesis, Norwegian University of Science and Technology (NTNU), Trondheim.

Knutsen, M. 2014. *On determination of Gmax by bender element and cross-hole testing*. Masters thesis, Norwegian University of Science and Technology (NTNU), Trondheim.

Konishi, C. 2015. Representation of the resistivity model using volume fraction of porous clay. *In*: *12th SEGJ International Symposium, Tokyo*.

Kornbrekke, H.A. 2012. *Stability evaluation of Rissa clay slopes based on block samples*. Masters thesis, Norwegian University of Science and Technology, Trondheim.

Lecomte, I., Bano, M., Hamran, S.-E., Dalsegg, E. & Nielsen, K.M. 2008*a*. Mapping quick clay sites for geohazard assessment: the Finneidfjord case study, Norway. *In*: *Near Surface 2008 – 14th European Meeting of Environmental and Engineering Geophysics, Kraków*, Paper B19. Q21

Lecomte, I., Bano, M. *et al.* 2008*b*. Submarine slides at Finneidfjord (Norway): geophysical investigations. *In*: *21st EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems*, 376–388. Q22

L'Heureux, J.-S., Longva, O. *et al.* 2011. Identification of weak layers and their role for the stability of slopes at Finneidfjord, Northern Norway. *In*: al., Y.Y.e. (ed.) *5th International Symposium on Submarine Mass Movements and Their Consequences, Kyoto*. Springer, Berlin, 321–330. Q23

Loke, M.H. 2016. RES2DINV version 4.05. Geoelectrical Imaging 2D and 3D. Instruction Manual. Geotomo Software, http://www.geotomosoft.com

Loke, M.H. & Barker, R.D. 1996. Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophysical Prospecting*, **44**, 131–152.

Long, M., El Hadj, N. & Hagberg, K. 2009. Quality of conventional fixed piston samples of soft clay. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, **135**, 185.

Long, M., Donohue, S. *et al.* 2012. Relationship between electrical resistivity and basic geotechnical parameters for marine clays. *Canadian Geotechnical Journal*, **49**, 1158–1168.

Longva, O., Janbu, N., Blikra, L.H. & Bøe, R. 2003. The 1996 Finneidfjord slide: seafloor dynamics. *In*: *First International Symposium on Submarine Mass Movements and their Consequences EGS–AGU–EUG Joint Meeting, Nice*. Kluwer, Dordrecht, 531–538. Q24

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

Lunne, T., Long, M. & Forsberg, C.F. 2003. Characterisation and engineering properties of Onsøy clay. *In*: *Proceedings, International Workshop on Characterisation and Engineering Properties of Natural Soils, Singapore*. Balkema, Rotterdam, 395–427. Q25

Mitchell, J.K. & Soga, K. 2005. *Fundamentals of Soil Behaviour*, 3rd edn. Wiley, Hoboken, NJ.

Montafia, A. 2013. *Influence of physical properties of marine clays on electric resistivity and basic geotechnical parameters*. Masters thesis, Norwegian University of Science and Technology (NTNU), Trondheim.

Moum, J. 1965. Falling drop used for grain-size analysis of fine grained materials. *Sedimentology*, **5**, 343–347.

Moum, J., Løkken, T. & Torrance, J.K. 1971. A geochemical investigation of the sensitivity of normally consolidated clay from Drammen, Norway. *Géotechnique*, **21**, 329–340.

Moum, J., Løken, T. & Torrance, J.K. 1972. Discussion on 'A geochemical investigation of the sensitivity of normally consolidated clay from Drammen Norway'. *Géotechnique*, **22**, 542–544.

NGF 2011. *Veilding for symboler og definisjoner i geoteknikk – identifisering og klassifisering av jord – Melding Nr. 2, Revidert 2011*. Norwegian Geotechnical Society (Norsk Geoteknisk Forening), Oslo.

Nordal, S., Alén, C., Emdal, A., Jendeby, L., Lyche, E. & Madshus, C. 2009. *Skredet i Kattmarkvegen i Namsos 13. mars 2009. Rapport fra undersøkelsesgruppe satt ned av Samferdselsdepartementet*. Institutt for Bygg, Anlegg og Transport, Faggruppe for Geoteknikk, NTNU, Trondheim.

Norwegian Standardisation System. 1988. *NS 8015 Falling cone tests*. Norwegian Standardisation System, Oslo.

Ottesen, H.B. 2009. *CPTU med resistivitietsmåling*. MSc thesis, *Norwegian University of Science and Technology (NTNU)*, Trondheim.

Øveraas, A.T. 2016. *A laboratory study of salt diffusion and its effect on electric resistivity and sensitivity in quick clay*. Masters thesis, *Norwegian University of Science and Technology (NTNU)*, Trondheim.

Palacky, G.J. 1987. Resistivity characteristics of geologic targets. *In*: Nabighian, M.N. (ed.) *Electromagnetic Methods in Applied Geophysics Theory, Vol. 1*. Society of Exploration Geophysicists, Tulsa, OK, 53–129.

Penner, E. 1965. A study of sensitivity in Leda clay. *Canadian Journal of Earth Sciences*, **2**, 425–441.

Pfaffhuber, A.A., Bastani, M. *et al.* 2010. Multi-method high resolution geophysical and geotechnical quick clay mapping. *In*: *Near Surface 2010 – 16th European Meeting of Environmental and Engineering Geophysics, Zurich*. Q26

Pfaffhuber, A.A., Bazin, S. *et al.* 2016. *In situ* detection of sensitive clays from a geophysical perspective. *In*: *5th International Conference on Geotechnical and Geophysical Site Characterisation (ISC'5), Gold Coast, Australia*. Q27

Puakowski, S. 2015. *Interpretation methods of CPTU and RCPTU with special focus on soft soils in Norway*. Masters thesis, *Norwegian University of Science and Technology (NTNU)*, Trondheim.

Rhoades, J.D., Raats, P.A.C. & Prather, R.J. 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. *Journal of the American Soil Science Society*, **40**, 651–665, https://doi.org/10.2136/sssaj1976.03615995004000050017x

Rømoen, M., Pfaffhuber, A.A., Karlsrud, K. & Helle, T.E. 2010. Resistivity on marine sediments retrieved from RCPTU soundings: a Norwegian case study. *In*: Robertson, P.K. & Mayne, P.W. (eds) *Proceedings 2nd International Symposium on Cone Penetration Testing (CPT'10)*. Omnipress, Huntington Beach, CA, 289–296.

Sandven, R. 1990. *Strength and deformation properties of fine grained soils obtained from piezocone tests*. PhD thesis, Norges Tekniske Høgskole (now NTNU).

Sandven, R., Ørbech, T. & Lunne, T. 2004. Sample disturbance in highly sensitive clay. *In*: *Proceedings of the 2nd International Conference on Geotechnical and Geophysical Site Characterisation – ISC'2, Porto*. Millpress, Rotterdam, 1861–1868. Q28

Sandven, R., Solberg, I.L., Hansen, L. & Hove, S.E. 2013. Geophysical and geotechnical investigations for a major highway in a quick clay area. *In*: L'Heureux, J.-S., Locat, A., Leroueil, S., Demers, D. & Locat, J. (eds) *Proceedings of the International Workshop on Landslides in Sensitive Clays (IWLSC) "From Geoscience to Risk Management", University of Laval, Québec City*. Springer, Dordrecht.

Sauvin, G., Bazin, S., Vanneste, M., Lecomte, I. & Pfaffhuber, A.A. 2011. Towards joint inversion/interpretation for landslide-prone areas in Norway – integrating geophysics and geotechnique. *In*: *Near Surface 2011 – 17th European Meeting of Environmental and Engineering Geophysics, Leicester, UK*, Paper E11. Q29

Sauvin, G., Lecomte, I., Bazin, S., L'Heureux, J.-S. & Vanneste, M. 2013*a*. Geophysical data integration for hazard assessment of quick-clay landslide prone areas: the Hvittingfoss case study, Norway. *In*: L'Heureux, J.-S. & Leroueil, S. (eds) *Proceedings of the International Conference on Landslides in Sensitive Clays (ICLSC), University of Laval, Quebéc City*. Q30

Sauvin, G., Lecomte, I., Bazin, S., L'Heureux, J.-S., Vanneste, M., Solberg, I.-L. & Dalsegg, E. 2013*b*. Towards geophysical and geotechnical integration for quick clay mapping in Norway. *Journal of Near Surface Geophysics, EAGE*, **11**, 613–623, https://doi.org/10.3997/1873-0604.2012064

Sauvin, G., Lecomte, I., Bazin, S., Hansen, L., Vanneste, M. & L'Heureux, J.-S. 2014. On the integrated use of geophysics for quick-clay mapping: The Hvittingfoss case study, Norway. *Applied Geophysics*, **106**, 1–13.

Shevnin, V., Mousatov, A., Ryjov, A. & Delgado-Rodriquez, O. 2007. Estimation of clay content in soil based on resistivity modelling and laboratory measurements. *Geophysical Prospecting*, **55**, 265–275.

Solberg, I.-L., Rønning, J.S., Dalsegg, E., Hansen, L., Rokoengen, K. & 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**, 210–225.

Solberg, I.-L., Hansen, L., Rønning, J.S., Haugen, E.D., Dalsegg, E. & 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**, 119–133.

Solberg, I.L., Long, M., Baranwal, V.C., Gylland, A.S. & Rønning, J.S. 2016. Geophysical and geotechnical studies of geology and sediment properties at a quick-clay landslide site at Esp, Trondheim, Norway. *Engineering Geology*, **208**, 214–230.

Swedish Geochechnical Institute. 1946. *Korfattat compedium i geoteknikk Meddelande Nr. 1*. Swedish Geotechnical Institute (SGI), Stockholm.

Syversen, F.S.G. 2013. *Et studie av den mineralogiske sammensetningen i norske sensitive leirer*. Masteroppgave i Geofag Studieretning, Miljøgeologi og Geofarer, Institutt for Geofag Matematisk-naturvitenskaplig fakultet, Universitetet i Oslo.

Torrance, J.K. 1983. Towards a general model of quick clay development. *Sedimentology*, **30**, 547–555.

van Olphen, H. 1977. *Clay Colloidal Chemistry*, 2nd edn. Wiley, Hoboken, NJ.