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ORIGINAL PAPER

Combined geophysical and geotechnical approach to ground investigations and hazard zonation of a quick clay area, mid Norway

Inger-Lise Solberg · Louise Hansen · Jan Steinar Rønning · Ellen D. Haugen · Einar Dalsegg · Jan Fredrik Tønnesen

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Abstract Mapping of quick clay is important for hazard zonation, planning and protection purposes. The present study focuses on an area prone to quick clay landslides in mid Norway, which is investigated through a combination of geophysical and geotechnical methods. The following classes are suggested for a first-order interpretation of resistivity profiles in areas with few or no previous investigations: Unleached clay deposits: 1–10 Ωm; Leached clay deposits, possibly quick: 10–100 Ωm; Dry crust clay deposits and coarse sediments: >100 Ωm. In the study area, 14–80 Ωm was found as the main resistivity interval for quick clay. The resistivity values from the present study are compared to previously published values. Classification of material from resistivity values is influenced by local conditions, and there is an overlap between the classes. Resistivity profiles can give valuable information for hazard zonation and may assist in maximising subsequent intrusive investigations.

I.-L. Solberg
SINTEF Building and Infrastructure, Rock and Soil Mechanics, Trondheim, Norway

I.-L. Solberg (✉) · L. Hansen · J. S. Rønning · E. Dalsegg · J. F. Tønnesen
Geological Survey of Norway, P.O. Box 6315 Sluppen, 7491 Trondheim, Norway
e-mail: inger-lise.solberg@ngu.no

J. S. Rønning
Department of Petroleum Technology and Applied Geophysics, NTNU, 7491 Trondheim, Norway

E. D. Haugen
Norwegian Geotechnical Institute, P.O. Box 1230 Sluppen, 7462 Trondheim, Norway

Keywords Resistivity · Geotechnical investigations · Marine sediments · Quick clay · Norway

Résumé La cartographie des argiles sensibles est importante pour des objectifs de zonage d'aléa, de planification et de protection. L'étude présentée se focalise sur une région sujette aux glissements dans des argiles sensibles du centre de la Norvège. Elle a mis en œuvre une combinaison de méthodes géophysiques et géotechniques. Les classes suivantes sont suggérées pour une première interprétation en termes de profils de résistivité dans des régions peu ou pas étudiées jusqu'alors : Dépôts d'argiles non lessivées : 1–10 Ωm; Dépôts d'argiles lessivées, pouvant être sensibles : 10–100 Ωm; Dépôts d'argiles superficielles sèches : >100 Ωm . Dans la région d'étude, des plages de valeurs de 14 à 80 Ωm caractérisent le mieux des argiles sensibles. Les valeurs de résistivité de cette étude sont comparées à des valeurs précédemment publiées. Le classement des matériaux à partir des valeurs de résistivité est influencé par des conditions locales et il y a un chevauchement entre les classes. Les profils de résistivité peuvent donner une information valable pour un zonage d'aléa et peuvent permettre d'optimiser des investigations ultérieures par méthodes intrusives.

Mots clés Résistivité · Investigations géotechniques · Sédiments marins · Argile sensible · Norvège

Introduction

Thick, marine clay deposits in valleys along the Norwegian coast are occasionally subjected to large, destructive quick clay landslides. An understanding of the ground conditions and the mapping of Holocene deposits, including an indication of the presence of quick clay, is therefore important for the evaluation of landslide hazards for planning and protection purposes. Numerous and expensive investigations may be necessary to obtain a detailed picture of the subsurface by the use of traditional drilling techniques and sampling. However, 2D resistivity measurements give a continuous and relatively detailed picture of the subsurface within a short time. 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 (e.g. Solberg et al. 2008). 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 use of 2D resistivity measurements as a tool for identifying quick clay has expanded during the last 10 years in Norway, Sweden and Canada (e.g. Calvert and Hyde 2002; Leroux and Dahlin 2003; Dahlin et al. 2005; Solberg et al. 2008; Donohue et al. 2009; Lundström et al. 2009). The development of measuring equipment and software for data processing, such as the inversion method (Loke 2007), has made the investigations easier and faster, and the results more reliable.

Traditionally, topographical maps combined with Quaternary geological maps, geotechnical data and hydrological data are used to identify areas where quick clay could be a problem (Viberg 1984; Gregersen 2002). Maps showing hazard and risk have been made for several clay slide-prone areas in Norway (www.skrednett.no). According to international standards (e.g. ISSMGE TC32 2004; Glade et al. 2005), Norwegian hazard maps are susceptibility maps, as the temporal aspect is difficult to address (e.g. Karlsrud et al. 1985). Risk has been considered the product of hazard and consequence (Gregersen 2002). Quick clay hazard zones in Norway are further evaluated if the hazard and risk levels are too high. This includes some geotechnical drilling and sampling as well as stability analyses. Zonation of areas prone to quick clay landslides is also carried out in Sweden and Canada (see e.g. Lebuis et al. 1983; Viberg 1984; Carson and Geertsema 2002; Robitaille et al. 2002; Lundström and Andersson 2008; Quinn 2009).

Previous studies of the capability of 2D resistivity measurements to map the extent of quick clay deposits are promising (Solberg et al. 2008, 2010; Donohue et al. 2009; Lundström et al. 2009). However, the application of the method for this purpose is still in its infancy and experience is relatively low. One purpose of the present study is to add to the experience and to further test the capability of the 2D resistivity method to delineate quick clay, through comparison with geotechnical data. Another purpose is to explore how 2D resistivity measurements can contribute to the evaluation of quick clay areas and hazard zonation. This includes the location of quick clay and other marine deposits within slopes for zone limitation and the detection of other sediments/bedrock that may reduce the size of a potential landslide. The classification of sediments and their properties using resistivity values are also discussed and values are compared with those obtained in other studies.

Setting

The study area is located in Gauldalen, about 15 km south of the city of Trondheim, mid Norway (Fig. 1). The area is characterised by thick clay and silt deposits that accumulated following the last de-glaciation. To the northeast is a large ice-marginal deposit which accumulated in front of an ice lobe from the southeast during the Younger Dryas stadial between 10,800–10,500 years BP (Reite et al. 1982). Part of the deposit accreted to the marine limit (ML, the highest relative sea level after the last glaciation) which is about 175 m above the present sea level (Reite 1983). The ice-marginal deposit consists of thick sand and gravel and is partly covered by marine clay. In the southeast of the study area is a small, local glaciofluvial deposit at ML (sourced from the Vassfjellet mountain). Above ML are glacial deposits and partly exposed bedrock (Fig. 1); the bedrock types in the area are green schist and amphibolite (Wolff 1976). Due to the glacio-isostatic rebound, the (glacio-) marine clays and silts are now found at up to 110–120 m a.s.l. Quick clay has developed within the fine-grained deposits as a result of leaching of the marine salts, which is highly dependent on the movement of groundwater through the sediments (e.g. Janbu et al. 1993).

The terrain is typical of clay areas in Norway: undulating with numerous landslide scars and ravines (Figs. 2a, 3). Several landslides have involved quick clay, which completely liquefies when disturbed. Some landslide scars are partially erased due to agricultural levelling, but are recognisable from old air photos. The largest scar is from the Jesmo landslide which occurred around 1650 to the north of the study area (Grønlie 1953; Fig. 2a) while another significant landslide occurred close to the railroad in 1867 (Railroad Operation Report 1867). Fieldwork along the Stokkbekken stream shows active erosion, especially west of the railroad (Fig. 2b). In the slope southwest of the stream there has been a relatively recent slope failure with the back scar almost at the top of the slope (Fig. 2a). Numerous scars of unknown age have been mapped; larger landslide scars have probably been modified by younger events.

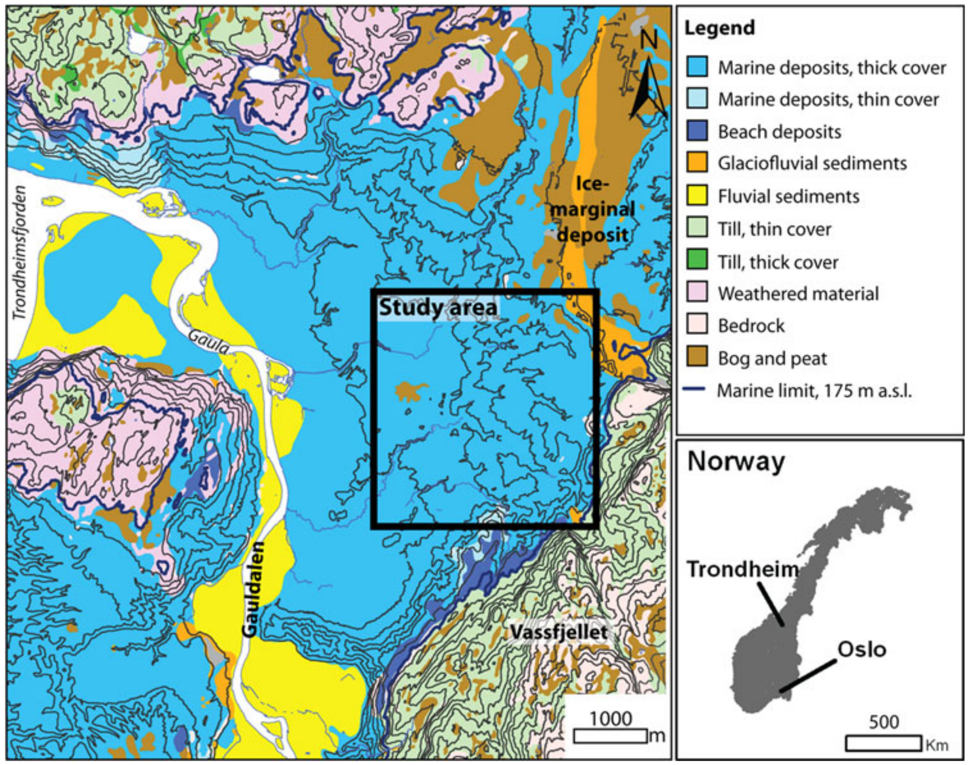


Fig. 1 Quaternary geology map (modified from Reite 1983). Contour interval: 25 m

Several quick clay hazard zones have been identified within the study area. The largest are Rødde, Stokkaunet and Litj-Ler (Fig. 2a) (Gregersen and Løken 1988; Eggen and Gregersen 2004; www.skrednett.no). These three zones have high hazard levels due to the presence of quick clay, active stream erosion and unfavourable topographical conditions.

Methods

2D resistivity measurements

Two-dimensional resistivity measurements were carried out based on the Lund-system developed by Dahlin (1993). Four active cables were used with the Gradient and Wenner (Wenner-α) electrode arrays (Reynolds 1997; Dahlin 1993). The measuring equipment was an ABEM Terrameter SAS 4000 (ABEM 1999), using a current of 100 or 200 mA. The steel electrode separations were 5 and 10 m (Dalsegg 2008) and the grounding connections were very good. Seven resistivity profiles were measured in the study area, with three of the profiles intersecting each other—P1, P4 and P5 (Figs. 2b, 4; Table 1). Profile 2 is located along the same line as Profile 1, but is shorter and with a different electrode spacing. Data quality was generally very good. A few measurements above the acceptable noise level (of 20%) were deleted before processing. The Gradient array gives more details than the Wenner array in a shorter time (Dahlin and Zhou 2006) and is the focus of the present study.

Raw data from the resistivity measurements give the apparent resistivity (ρ_a) of the subsurface. This represents a weighted mean of all the resistivity values that fall within the soil volume of influence. To obtain the specific resistivity (ρ) in Ωm from different parts of the subsurface, the data are inverted. The purpose is to produce an apparent resistivity pseudo-section that matches the measured data. Recorded resistivities were inverted by the computer program Res2DInv, using the least-squares method (Loke 2007). The inversion was executed with a vertical to horizontal flatness filter ratio of 0.5, which emphasises horizontal structures in the subsurface. Most of the data shown are from Smooth inversion (standard), but Robust inversion was also used for comparison as it better detects sharp boundaries (e.g. between clay and bedrock, see Reiser et al. 2010). The three intersecting profiles were separately inverted and thereafter displayed in the ESRI software ArcScene for comparison, with the scaling of the different profiles equal.

When interpreting a profile it is important to be aware that the most reliable data are in the top and centre of the profile, due to the higher resolution. Along the outer edges and at depth there are less data. Solberg et al. (2008) made a classification of sediments from 2D resistivity measurements in a similar setting, and this was used for preliminary

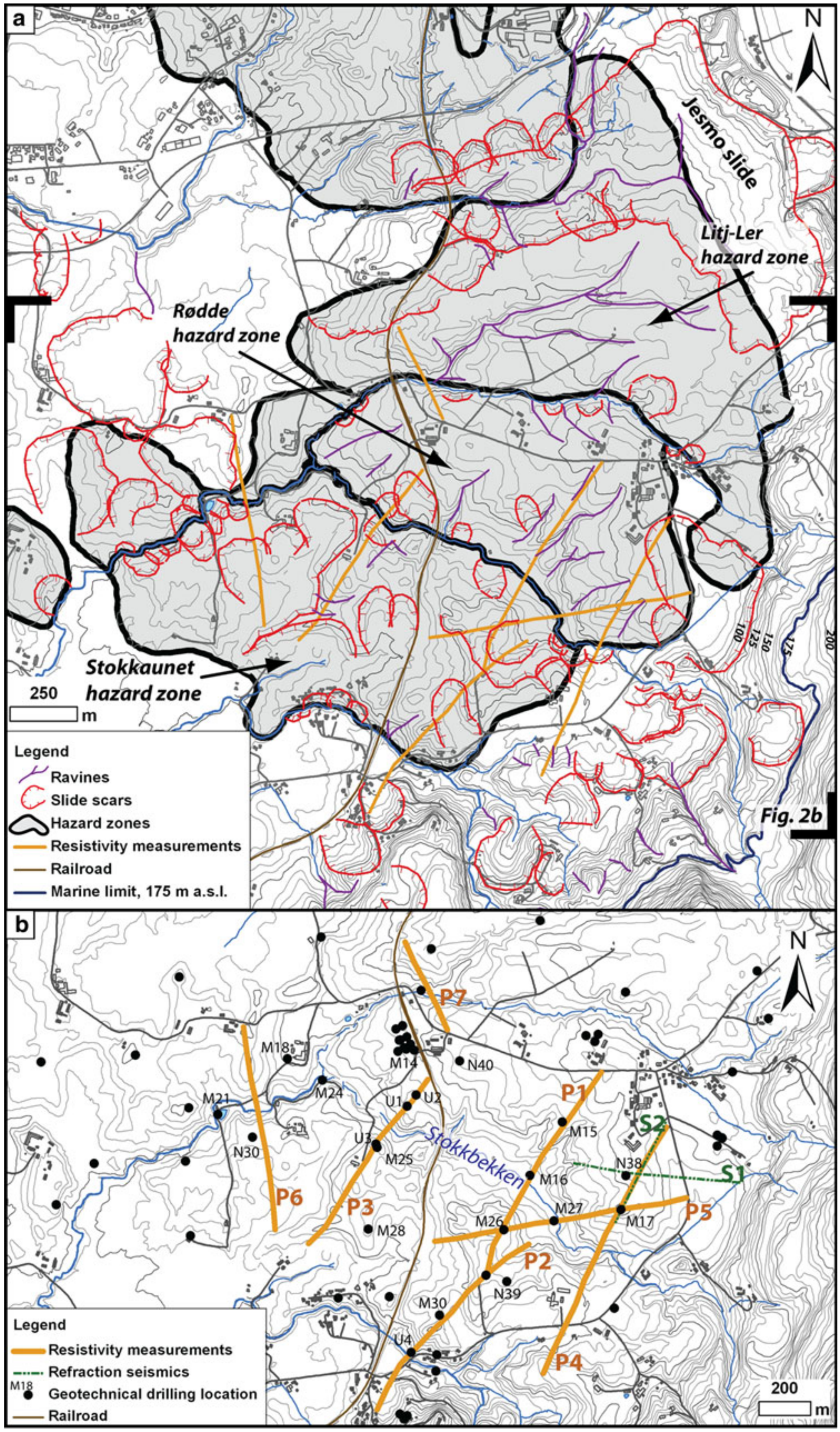


Fig. 2 **a** The study area with predefined hazard zones and mapped landslide scars. Contour interval: 5 m. **b** Overview of the geophysical and geotechnical investigations carried out in the study area. The drillings were made by different companies from 1978 to 2010. Labelled drillings: *M* Vik and Havnegjerde (2010), *N* Gregersen and Løken (1988), *U1–U3* Ottesen (2009), *U4* NTNU. Contour interval: 5 m

Fig. 3 The study area looking towards the northwest. Typical Norwegian clay terrain with landslide scars and ravines

interpretations in the present study (Table 2). The classification is discussed below, as local conditions may influence the resistivity values of different sediment types and properties, as shown from recent studies (e.g. Rømoen et al. 2010).

Refraction seismic measurements

The seismic refraction method records the travel time of refracted seismic waves in the subsurface. Velocities of materials vary from 200 m/s (loose sand) to more than 7000 m/s (crystalline rock); see Telford et al. (1990). Clay generally has a higher velocity than dry sand, but if the sand is saturated it is difficult to separate from clay. Different layers in the subsurface can only be distinguished when the velocity of the layers increases with depth. Even if this condition is met, a thin layer can be hidden—referred to as the blind zone by Reynolds (1997).

Two refraction seismic profiles were carried out in the area (Tønnesen 2010). The profiles are 660 m (S1) and 440 m (S2) long, and were carried out primarily to locate potentially coarse sediments and depth to bedrock (Fig. 2b). The 24 channel digital seismograph ABEM Terraloc MK6 was used and 3 (S1) and 2 (S2) arrays along the profile were measured. Dynamite (50–100 g) was used as the energising source.

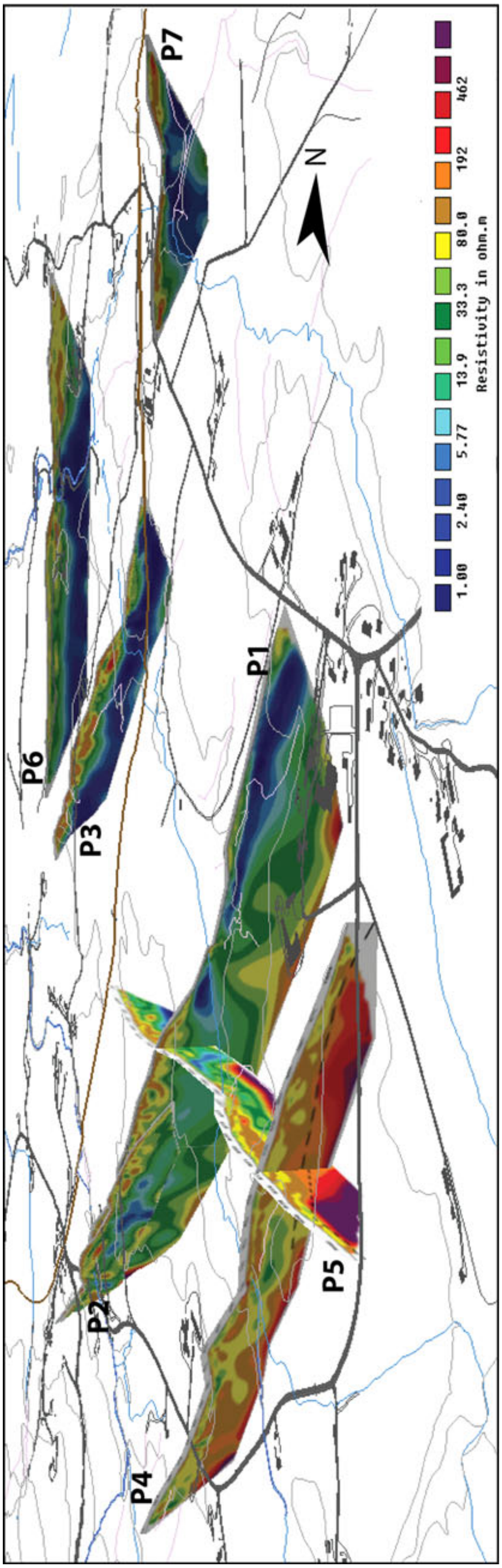
Geotechnical investigations

Ground conditions in the study area have been investigated by different consulting companies from 1978 to 2010. The methods used are Core Sampling (with laboratory testing), Rotary Pressure Sounding (RPS), Cone Penetration Test Undrained (CPTU), Total Sounding (TS), Rotary Sounding, Vane Shear Tests and Pore Pressure Measurements. Of the sounding methods, CPTU give the best information on sediment stratification and soil type. RPS is often used to detect quick clay and TS may be used to verify depth to bedrock. Laboratory tests on material from core samples give detailed information on sediment stratification, soil type, shear strength, deformation properties, permeability, etc. For further descriptions of the geotechnical methods and interpretation, see, e.g. Gregersen and Løken (1983) and Sandven (2002).

A few tests with an electrical conductivity adapter from Geotech (2010), attached to a conventional CPTU (called RCPTU, 1D resistivity measurements), were carried out in the study area (Ottesen 2009). There are four ring electrodes in the adapter (Wenner configuration) and an electric transmitter. The probe is 44 mm in diameter and is pushed into the ground in the same way as other CPT probes. Readings are taken every second. In the present study measured resistivity values from Ottesen (2009) were calibrated using a calibration factor of 2.28 (Aasland 2010) as the probe systematically gives too low resistivity values.

Geotechnical classification of quick clay

Sensitivity (S_t) is defined as the undisturbed shear strength divided by the disturbed shear strength. When the remoulded shear strength (s_r) is less than 0.5 kN/m^2, the clay is characterised as “quick”. The standard Norwegian classification of sensitive clay is divided into low sensitivity: $S_t < 8$; medium high sensitivity: $8 < S_t < 30$; high sensitivity (quick clay): $S_t > 30$ (NGF 1975). The Norwegian Water Resources and Energy Directorate



◀ **Fig. 4** Quasi-3D visualisation of all the 2D resistivity profiles in the study area, seen from the northeast. *Dashed lines* (in P4 and P5) indicate bedrock interpreted from refraction seismic measurements. See Table 2 for colour interpretations and Fig. 2b for details on profile locations. Contour interval 25 m

(NVE) has developed guidelines for hazard zonation in quick clay areas (NVE 2009) and recommends that clay with a sensitivity $S_t \geq 15$ and remoulded shear strength $s_r < 2$ kPa is classified as sensitive clay, which has the potential of brittle fracture, i.e. can lead to quick clay landslides. This definition of sensitive clay includes a broader range than the traditional classification. Unless otherwise stated, the standard definition of sensitivity (NGF 1975) is used in the present study.

The natural salt content in seawater is about 35 g/l. When clay with salt pore water is leached by fresh groundwater, the salt content in the pore water is reduced. When the salt content is reduced below 5 g/l, the marine clay can become sensitive and show quick clay behaviour (Bjerrum 1954). In the present study salt contents were measured on samples from only two drillings (U1 and U4) as measurement of pore water salt contents in laboratory tests is not a standard procedure.

Results

General profile descriptions from the geophysical investigations

The seven 2D resistivity profiles acquired show that low resistivity values (ca. 0–100 Ωm) dominate and that high resistivity values (>200 Ωm) are present in P4 and P5 and in the lower part of P1 (Fig. 4). In all profiles, except for P4, there are also one or more 5–10 m thick pockets with high resistivity (~400 Ωm) close to the surface (15 m), within material generally of 10–200 Ωm. Most of P1 and P2 show resistivity values between 10 and 100 Ωm. P3, P6 and P7 all have a lateral continuous layer of low resistivity values (1–10 Ωm), mainly below stream level. All the resistivity profiles, with both electrode configurations, are presented in detail in Dalsegg (2008).

There is generally good agreement between intersecting and overlapping resistivity profiles, especially in the upper parts. For the overlapping profiles P2 and P1 the lower parts of each profile show similar resistivity, although the depth to the same resistivity layers is different. This is probably caused by the inversion technique applied. For the overlap of profiles P4 and P5 the shape of the high resistivity layers in the lowermost part of the profiles differs

Table 1 2D resistivity profiles measured in the study area

Profile no.	Profile length (m)	Electrode configuration		Electrode spacing (m)	Approximate penetration depth (m)	Relative resolution
		Gradient	Wenner			
P1	1600	X	X	10	130	Low
P2	800	X	X	5	60	Moderate
P3	800	X	X	5	60	Moderate
P4	1100	X		5	60	Moderate
P5	1000	X		5	60	Moderate
P6	800	X		5	60	Moderate
P7	400	X		5	60	Moderate

For location of profiles, see Fig. 2

Table 2 Preliminary sediment classification from resistivity values (modified from Solberg et al. 2008)

Resistivity (Ωm)	Main characterisation	Description	Colour code
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 stabilises 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. Conductive minerals like graphite and sediments saturated with water rich in ions may also give low resistivity values	Blue-toned colours
10–80	Leached clay deposits	Sensitive clay develops as groundwater leaches ions from the marine clay. When the total electrolyte content is less than ca. 5 g/l, quick clay may form. 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: non-quick but leached marine clay, silt, and fine-grained till	Green-yellow
>80	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 Ωm	(Yellow)-orange-red-(purple)

Note that there are gradual transitions between the classes and there may be local variations related to such factors as pore water chemistry, saturation, mineral composition, etc.

(Fig. 5a). This can be explained by geometric variations in the geology (see also Solberg et al. 2008). Some inconsistency is seen in the lowermost part of the overlap of P1 and P5 (Fig. 5b), probably due to the difference in electrode spacing and therefore resolution, and/or 3D effects. The conformity was better when Robust inversion was used.

The refraction seismic profiles S1 and S2 show a thin top layer with a velocity of 300–750 m/s overlying sediments with a velocity of ca. 1400–1600 m/s above bedrock with velocities mostly of 5100–5900 m/s. S1 shows a bedrock depression in the eastern part of the profile, and here the bedrock has a lower velocity (ca. 2300 m/s). The sediment thickness increases towards the west in S1 (Figs. 4, 6). Profile S2 is located along the profile line of P4, while S1 is almost parallel to parts of P5 (Fig. 2b).

Geotechnical results

Numerous geotechnical data have been obtained in the study area (Fig. 2b). The geotechnical investigations north of Stokkbekken (M15, M17, N38) show homogeneous clay, partly silty with low sensitivity down to 30 m depth (in the area of the 2D resistivity profiles P1, P4 and P5). A 10 m layer of possible quick clay is present in M17 (Fig. 6). From 40 m depth is a coarser, more layered material. Further eastwards, towards the large ice-marginal deposit, drilling profiles show sand/gravel in the lower parts and/or coarse layers in the clay.

In the area of P3, P6 and P7 the geotechnical investigations identified up to 20 m quick clay above non-quick homogeneous clay (M14, N40, M18). Along the Stokkbekken stream, quick clay is recorded at 10–15 m below the river bed, overlying clay layered with coarser sediments (M27). Downstream there is also clay with coarser layers from 0 to 23 m and below 39 m (M16). Soundings west of P3 indicate homogeneous non-quick clay below the stream, with few coarser layers (M24, M21).

South of Stokkbekken, in the southern/western part of P1, P4 and P5, the investigations show generally 0–10 m non-quick clay over a 20–30 m layer of quick clay (e.g. M26, N39, M30). From 50 m depth are coarser sediments.

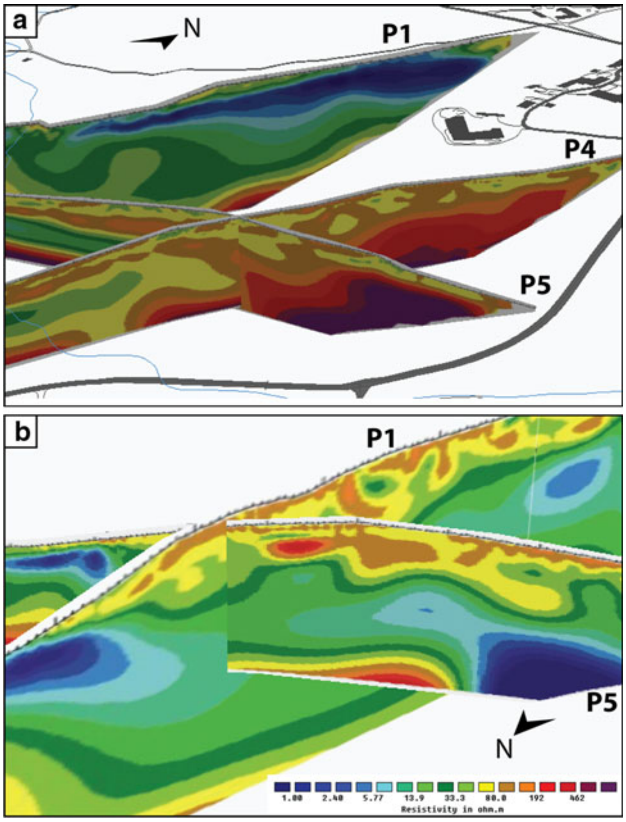


Fig. 5 Close-up of intersecting 2D resistivity profiles. There is generally good overlap agreement; see text for further descriptions/ comments

West of the railroad the quick clay layer is reduced to 10–20 m in thickness, with homogeneous clay below.

Geological interpretation

The low resistivity values (ca. 0–100 Ωm) of all seven profiles are interpreted as mainly representing clay deposits, consistent with the Quaternary map showing marine deposits at the surface (Fig. 1), and the drill data. High resistivity values are interpreted as representing coarser sediments and bedrock in the deeper part of the profiles towards the south and east (P1, P2, P4, and P5). This is consistent with the drillings, the presence of bedrock outcrops, and the nearby ice-marginal deposits (Gregersen and Løken 1988; Wangen and Sand 2007; Vik and Havnegjerde 2010; Fig. 1). The resolution in the resistivity profiles is too poor for the identification of thin sand/gravel layers in the clay, hence this type of information is retrieved only through drilling. However, a knowledge of the overall geology of the area helps the interpretation of the resistivity profiles, e.g. where coarse-grained layers could be expected.

Separation of bedrock and thicker accumulations of coarser-grained material is undertaken by changing the scale of the resistivity profiles, and comparison with the seismic profiles. However, the seismic results show relatively shallow bedrock, while the position of the bedrock is deeper according to the resistivity profiles (Figs. 4, 6). This may be partly due to the inversion technique (see Reiser et al. 2010), and partly to the better conductance in the clay leading to downward displacement of the high resistivity material. In addition, fractured bedrock and conductive minerals may give low bedrock resistivity values. Most of the sediments above bedrock have seismic velocities indicating clay or water-saturated coarser material, as confirmed by the intrusive site investigation work reported by Wangen and Sand (2007).

Resistivity values of marine clay deposits

Low resistivity clay deposits (unleached)

Clay deposits with low resistivity values (~1–10 Ωm) occur in all the profiles except P4. In P5 they appear only in the western part of the profile. The thickness of the low resistivity layers in the profiles increases towards the west. In P3 a continuous layer of low resistivity is present below stream level, except in the north where it also occurs in the slope surface (Fig. 7). The presence of this low resistivity layer is confirmed by the RCPTU data from U1 and U2 (Fig. 8). The samples also showed increasing pore water salt content with depth, with more than 5 g/l recorded below ca. 14 m (U1; Fig. 8). The corresponding resistivity values at this depth are 8–10 Ωm (1D) or 15 Ωm (2D), decreasing downwards. Low resistivity clay deposits are interpreted as unleached clay, as the high pore water salt contents give good conductivity.

Medium resistivity clay deposits (leached, possible quick clay)

Medium resistivity clay deposits occur in all the seven profiles (~10–100 Ωm) (Fig. 4). Quick clay, as interpreted from several drilling profiles, always corresponds to 2D resistivity values above 10 Ωm, and usually between 14 and 80 Ωm. A few drilling profiles indicate the presence of quick clay where 2D resistivity values of up to 200 Ωm were recorded (e.g. M25, M26; Figs. 6, 7).

Significant parts of P4 and the eastern part of P5 have resistivity values between 80 and 200 Ωm (Figs. 4, 6). These values may be explained by a high content of silt/sand/gravel within the clay, and/or reduced pore water salt contents. The presence of quick clay below firm clay is interpreted from drilling M17, located at the P4–P5 intersection (Figs. 2b, 6). The corresponding resistivity value in

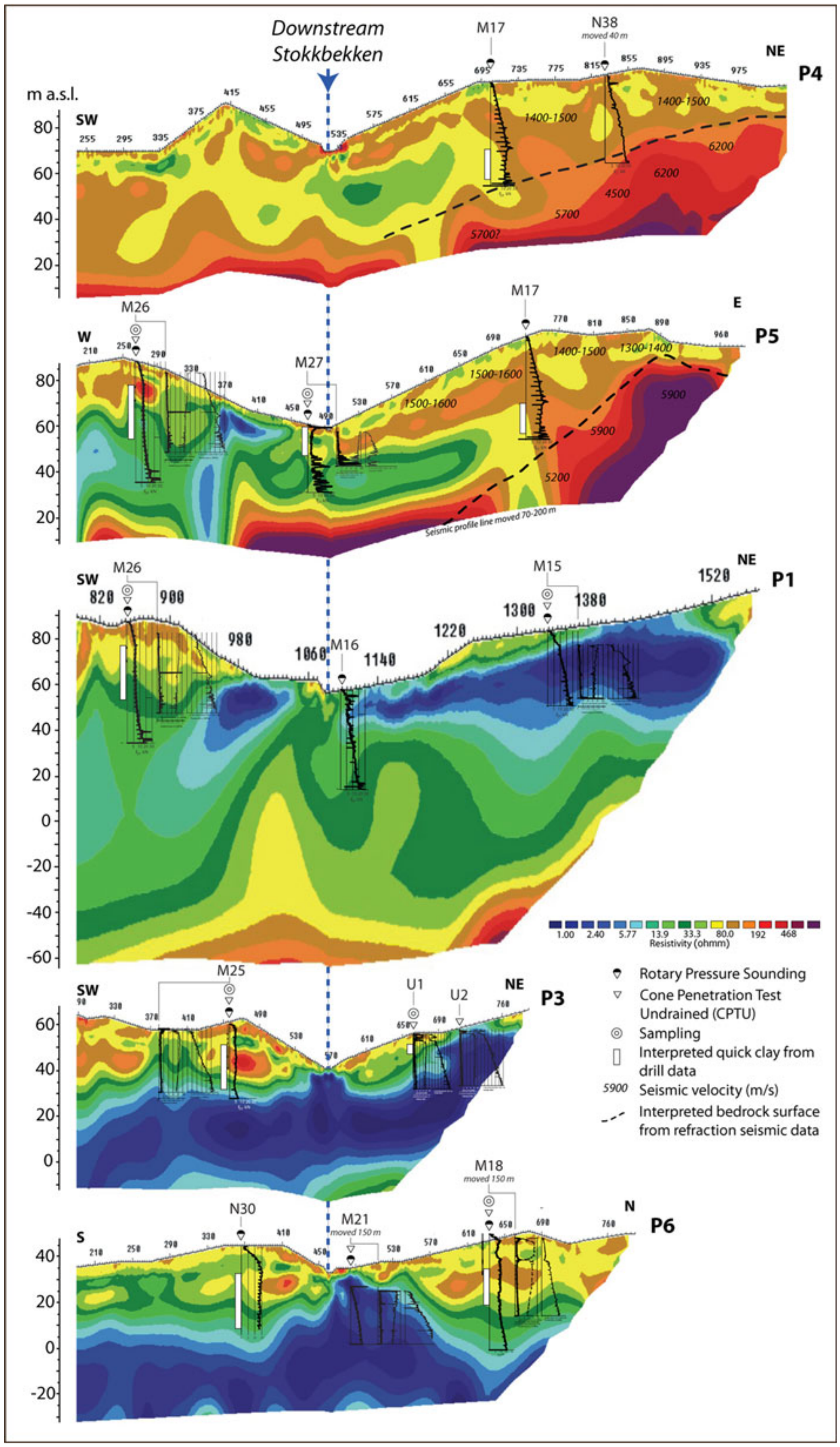


Fig. 6 Drilling profiles superimposed on 2D resistivity profiles downstream Stokkbekken. Interpreted quick clay from drill data is highlighted. See Fig. 2 for drilling references

the quick part of drilling profile M17 is 80 Ωm, with 100–200 Ωm in the firm layer above.

In P3 testing of samples from U1 indicated quick clay between 6 and 11 m depth, with medium sensitive clay below (Fig. 8). There is relatively good agreement between the two resistivity methods in U1 and P3; quick clay being indicated in the range of 15–60 Ωm in the RCPTU data while the corresponding 2D resistivity values are

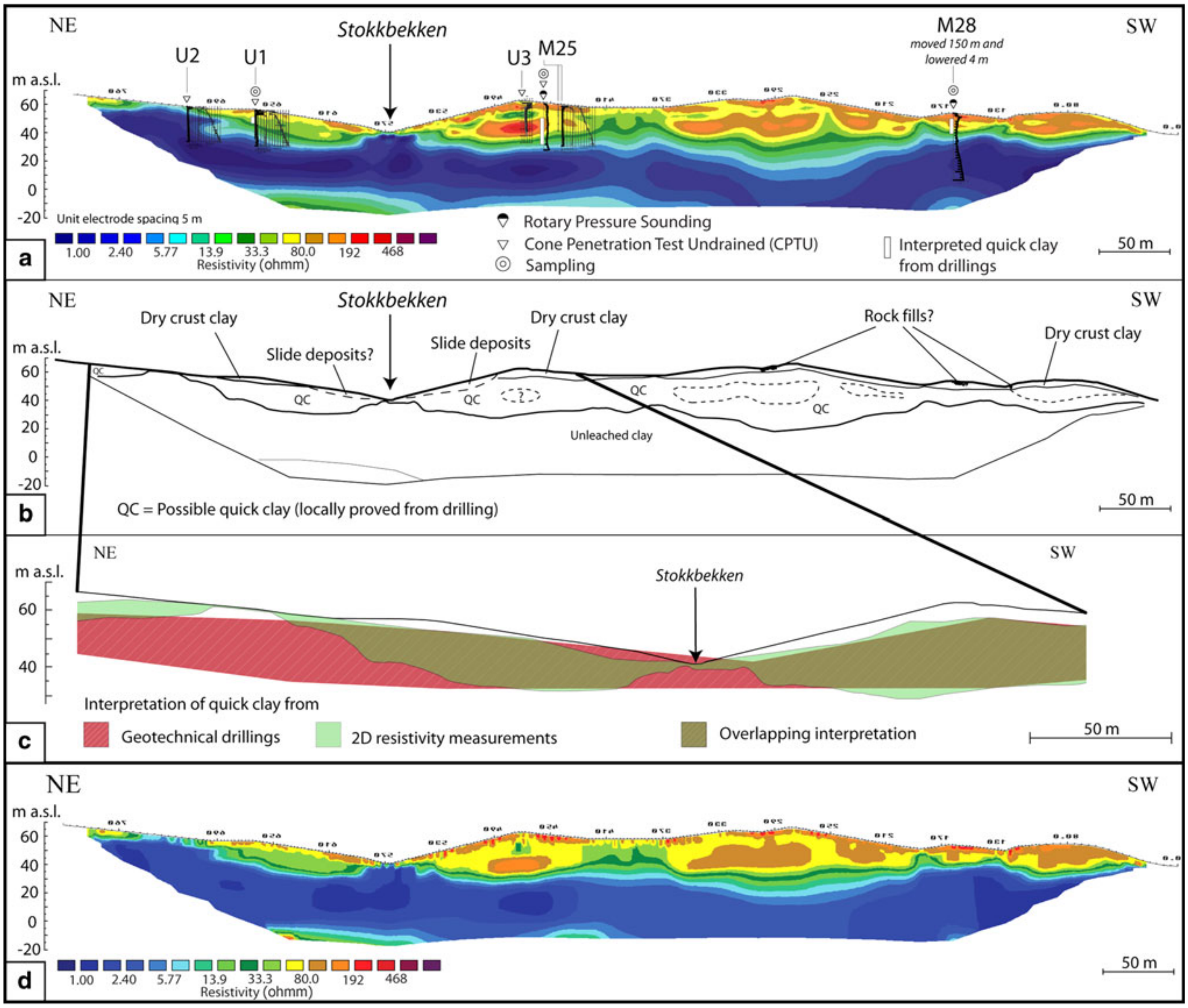


Fig. 7 **a** 2D resistivity profile (P3, standard inversion) with geotechnical drilling profiles (from Ottesen (2009); Vik and Havnegjerde (2010)). **b** Combined geotechnical and geophysical interpretation of P3. **c** Comparison of 7b and the assessment of quick clay extent based solely on drill data (based on NVE guidelines (NVE 2009)). **d** P3 with Robust inversion

25–50 Ωm. 2D resistivity values were also compared to sensitivity and salt content in U4 (P2). Here the resistivity is between 14 and 25 Ωm in the quick clay part of the sample (Fig. 8).

The medium resistivity values of clay are explained by leaching and quick clay development. The distribution of quick clay is therefore linked to the groundwater drainage patterns (Solberg et al. 2008). The amount of silt/sand/gravel layers within the clay will increase local groundwater movement. The small glaciofluvial deposit southeast of the study area possibly correlates to the coarse layers in the drill data close to Stokkbekken (M27, M16; Figs. 1, 2, 6). These coarse layers may be responsible for the increased leaching of the salts within the clays below Stokkbekken in resistivity profiles P1, P4 and P5. Alternating clay and saturated sand/gravel layers may locally give rise to relatively low resistivity values (P5 shows ca. 15–80 Ωm in almost the entire drilling profile M27).

Shallow depths to bedrock and/or interfingering/local coarse deposits control the groundwater drainage pattern in certain parts of the study area. Upward groundwater flow may result in significant leaching, which can explain the presence of quick clay below stream levels. In areas where the bedrock is at great depth and/or the clay is relatively homogenous, leaching and quick clay development mainly take place in stream slopes (Fig. 6).

The main interpretation of the profiles in the study area may be summarised as follows:

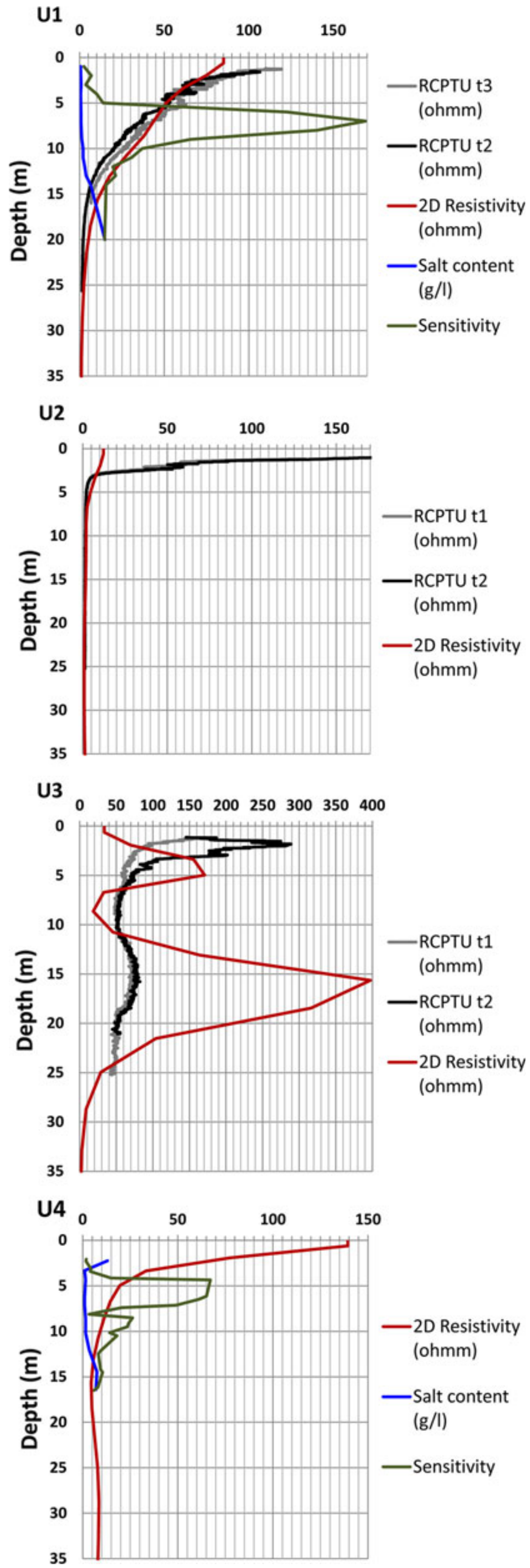


Fig. 8 Comparison of geotechnical and geophysical data for U1–U4 (see Fig. 2b for locations). Drill data are partly modified from Ottesen (2009)

- Profiles P4 and the eastern part of P5 are characterised by a relatively shallow bedrock and/or coarse material overlain by thoroughly leached clay with no or few unleached clay pockets.
- Profiles P1, P2 and the western part of P5 are characterised by a deeper bedrock and/or coarse material overlain by thoroughly leached clay, but with a layer/pockets of unleached clay remaining around stream level.
- In profiles P3, P6 and P7 no bedrock and/or coarse material can be recognised. Thick unleached clay mainly occurs below stream level.

High resistivity clay deposits (dry crust, landslide debris)

The upper 1–5 m of the profiles with resistivity values of 100–200 Ωm are in general interpreted as dry/desiccated clay crust. Some of the resistivity profiles cross landslide scars or run-out paths of old landslides (Fig. 2a). Parts of these profiles may be interpreted as landslide debris (e.g. in the north-facing stream slope in P3, Fig. 6). Erosion/sliding or agricultural levelling may have locally removed the high resistivity surface layer, revealing quick or unleached clay close to the surface.

The terrain in the study area is undulating with many small hills surrounded by slide scars or ravines. These hills have relatively high resistivity values (80–200 Ωm) probably due to the drying-out of these isolated areas, which also contain pockets of 10–80 Ωm. Drilling profiles here show 5–15 m firm clay above a 6–20 m thick quick clay layer (e.g. M18, M26, M28, N30; Figs. 2b, 6, 7).

The inversion procedure for the 2D resistivity data seems to be important for resistivity values. 400 Ωm lenses often occur in hills and generally above stream level. If Robust inversion is used, the resistivity values of the lenses give less than 200 Ωm (Fig. 7d). Locally, there are relatively large differences between 1D and 2D data (U3, P3; Fig. 8). In the 2D high resistivity lens, the 1D data (70 Ωm) are five to six times smaller using Smooth inversion and two to three times smaller using Robust inversion. The CPTU data in U3 shows a small variation throughout the lens (Ottesen 2009). This is also the case for the M25 data (drilled in the vicinity) where the samples and drilling profile proved clay with quick properties in the high resistivity area. Possible explanations for the high resistivity in this case may be the presence of adjacent boulders, coarse material, and/or landslide debris.

Table 3 Classification of clay properties from resistivity values in quick clay related studies from Norway, Sweden and Canada with suggestions on resistivity intervals for specific material properties (if made)

Material (Ωm)			Method	Country	Comment (e.g. data amount)	Reference
Unleached marine clay	Leached clay (potential quick)	Dry crust clay				
1–20	>5–10		1D	Sweden	Measurements with "salt probe"	Söderblom (1969)
	20–90	70–300	1D	Norway		Berger (1980)
	(ca.) 10–100		1D, 2D	Canada	2D: 2 profiles	Hyde and Hunter (1998), Calvert and Hyde (2002)
					1D: 2 drillings	
	>7		2D	Sweden	3 + 5 profiles (two sites)	Dahlin et al. (2001), Leroux and Dahlin (2003)
1–10	10–80	>80	2D	Norway	13 profiles	Solberg et al. (2008)
	10–80		2D	Norway	6 profiles	Donohue et al. (2009)
	>(6.3–16)		2D	Sweden	Data from different projects	Lundström et al. (2009)
					Suggested classification: Possible quick clay > 5	
	>3[a] (1D)		1D, 2D	Sweden	2D: 5 profiles	Schälin and Tornborg (2009)
					1D: 11 drillings	
					Corresponding 2D values are in general higher than 1D	
>5	5–20		1D	Norway	5 drillings (one showing quick clay)	Rømoen et al. (2010)
					Suggested classification: Unleached clay: 1–20, leached clay: 5–90, leached and weathered clay: 8–300	
	13–80		1D	Norway	8 drillings (three showing quick clay). 1D are compared with 2D	Aasland (2010)
	14–80[b] (2D)	>80 (2D)	2D, 1D	Norway	2D: 7 profiles	This study
	15–60 (1D)				1D: 3 drillings	
					Suggested classification: see text	

[a] Possible sulphide content in the clay or wrong calibration

[b] A few locations indicate quick clay where resistivity is down to 10 and as high as 200

Discussion

RCPTU versus 2D resistivity

The influence area of RCPTU is small due to short electrode separations, hence it gives site-specific details. This means that RCPTU is likely to measure relatively homogenous material in each reading. The apparent resistivity (ρ_a) is therefore interpreted to be equal to true resistivity (ρ) hence the data do not need to be inverted. Measurements with 2D resistivity produce apparent resistivity values that need to be inverted to calculate the true resistivity of the subsurface. The 2D measurements have long arrays with a relatively large influence volume, whereas areas of low resistivity will be preferentially identified and dominate the results. As both the sampling procedure and the data processing for 1D and 2D measurements differ, the material classification will vary. For example, the 2D resistivity values in the medium and highly sensitive clay are higher than the corresponding RCPTU values from U1 (Fig. 8). This is in agreement with the study of Fukue et al. (1999) showing that remoulded clay has better conductivity than undisturbed clay, as the breakage of the chemical bonding between the clay particles during drilling will decrease the resistivity.

1D and 2D data seem to agree well when the conditions are relatively uniform, with homogenous conditions (U2) or some layering (U1). In U3 the conditions are more complex, and there is less agreement. In such situations, it is likely that the RCPTU will give more reliable resistivities for a specific location, as the 2D measurements are more susceptible to 3D effects as exemplified above.

Classification of clay deposits from resistivity values

Table 3 shows the classification of the clay properties from resistivity values in quick clay related studies from Norway, Sweden and Canada. In general, quick clay does not give resistivity values below 5 Ωm in either 2D resistivity measurements or in RCPTU. A range of 10–80 Ωm for quick clay fits with the NVE classification of sensitive clay ($S_t \geq 15$ and $s_r < 2$ kPa, NVE 2009), but the inclusion of medium sensitive clay is a conservative approach. Dry crust clay, landslide debris (e.g. remoulded quick clay) may have values from 80 Ωm up to ca. 200 Ωm. Within the "quick clay range", the resistivity values could also represent other material such as leached marine clay that is not quick, silt or fine-grained till.

The classification of clay properties and other material based on resistivity values is mainly empirical, e.g. deduced from a comparison of geophysical and geotechnical data. 2D resistivity data are influenced by a relatively wide volume along the profile, and there will always be gradual transitions between high and low resistivity values in a profile. Caution should therefore be exercised with depth estimations. In addition, the geology and material properties themselves will often show gradual transitions and not always sharp boundaries. Nevertheless, the agreement between the intrusive sampling and laboratory measured properties and the 2D data is usually good.

Mapping clay properties by the use of resistivity

It is suggested that for an area without previous investigations, there is a need for a first-order classification which can act as a guideline for the interpretation of 2D resistivity profiles and for the planning of further surveys. The geotechnical drilling would preferably include RCPTU, for comparison with the 2D data. Thereafter, a refined site-specific classification can be made, taking into account the local mineralogical, geological and hydrogeological conditions, etc. From 2D resistivity measurements in the present study, quick clay is mainly interpreted to occur within the interval 14–80 Ωm, with a few indications of quick clay down to 10 Ωm and occasionally as high as 200 Ωm. For the few 1D measurements available, the quick clay interval is 15–60 Ωm.

Based on the present and other studies (Tables 2, 3), it is suggested that the following intervals are applied during first-order interpretation of resistivity profiles:

(a) Unleached clay deposits: 1–10 Ωm,
(b) Leached clay deposits, possibly quick: 10–100 Ωm,
(c) Dry crust clay deposits and coarser sediments: >100 Ωm.

This may be used as a basis for further investigations, with the awareness that local conditions may give higher or lower resistivity values for quick clay and that there may be some overlap between the classes.

In general, the geotechnical data fit well with the 2D and 1D resistivity data as shown in the present study. Even though the resistivity method cannot separate quick clay from other leached, but less sensitive clay deposits, it gives important indications of possible quick clay layers or pockets. Other important information can also be retrieved; for example large, continuous areas of unleached marine clay deposits may represent relatively stable areas.

1D and 2D resistivity data may also help to identify whether clay is leached or not, even if a sounding profile shows increased resistance with depth and thus stable conditions. This may be the case both where the clay has not been leached to a sufficient degree, or has passed the quick clay stage due to infiltration of stabilising ions present in the groundwater (Hilmo 1989).

Hazard zonation

The 2D resistivity profiles in the study area were placed within or crossed the borders of pre-defined hazard zones, for comparison with drill data and to further assess if the zones could be modified. The north-eastern part of P4 and P5, together with the seismic results, shows that bedrock is located at a shallow depth (Figs. 4, 6). The Rødde hazard zone could possibly be confined here. Both bedrock and, locally, thick unleached clay deposits (e.g. in the northern part of P1), could limit the extent of large clay landslides. Thick coarse-grained deposits were not detected in the areas of the measured resistivity profiles, but such deposits could also confine the extent of a landslide. A resistivity profile crossing the eastern limit of the Litj-Ler hazard zone into the large ice-marginal deposit could have been useful to outline the limits of clay versus coarser-grained deposits. The northern part of P6 is located between two small hazard zones (Fig. 2a). The resistivity profile indicates quick clay, suggesting the area could be included in a refined hazard zone.

The amount and position of quick clay in a slope is of great importance, as this may govern the extent of a potential quick clay landslide (Karlsrud et al. 1985). As shown above, resistivity profiles can give valuable information on variations in geology and different material properties. Without the 2D resistivity information, the extent of quick clay between geotechnical drilling profiles is always drawn conservatively when calculating slope stability, as shown in Fig. 7c. 2D resistivity profiles can provide more details on the geometry of a quick clay pocket between drill holes, which will then allow for more realistic stability calculations. For hazard zonation it is mainly the deposits below the land surface down to some level below the river which is of interest. It is unlikely that quick clay much deeper is affected by erosion or can be disturbed by human intervention. This should be considered when deciding the depth and resolution of planned 2D resistivity profiles.

Conclusions

A procedure is suggested for a first-order classification of clay properties from 2D resistivity profiles, based on the present study and previously published values: unleached clay deposits: 1–10 Ωm; leached clay deposits, possible quick clay deposits: 10–100 Ωm; dry crust clay deposits and coarse sediments: >100 Ωm.

After collection of additional data from geotechnical investigations, preferably including RCPTU (1D), a refined, site-specific classification can be established as resistivity values are influenced by local conditions.

For 2D resistivity measurements 3D effects play a role and hence 1D measurements may better reflect local variations.

Quick clay will occasionally have values outside the 10–100 Ωm interval, and the intervals between the classes overlap. In the present study 14–80 Ωm was the main resistivity interval for quick clay, and it was not detected below 10 Ωm.

For the correlation of drill data, for stability assessments and for hazard zonation it is important to delineate the extent of the quick clay and its position in the slope; 2D and 1D resistivity profiling can give valuable information on this and maximise the data which can be obtained from subsequent intrusive investigations, supported by laboratory studies.

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