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# Geophysical Mapping of Quick Clay - A Case Study from Smørgrav, Norway

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## SUMMARY

Marine clay deposits in coastal, post-submarine areas of Scandinavia and North America may be subjected to quick clay landslides. Quick clay may be described as highly sensitive marine clay, deposited in a marine environment during the last glaciation. In Norway some of the most densely inhabited areas, such as the areas around Oslo and Trondheim are located in potential quick clay areas and hence significant efforts are being taken to map its occurrence and extent. In this paper Electromagnetic (EM-31), Electrical Resistivity Tomography (ERT) and Multichannel Analysis of Surface Waves (MASW) methods were tested on a site known to contain quick clay. The site under investigation, Smørgrav, has a history of quick clay sliding, the most recent event occurring in 1984. A number of these approaches have proved promising, in particular ERT, which delineated a zone of quick clay that had previously been confirmed by rotary pressure soundings and borings.

## Introduction

A large amount of marine clay in the Northern Hemisphere that was deposited during the Pleistocene epoch, currently lies above sea level, as a result of isostatic uplift following deglaciation. The original marine depositional environment resulted in the sedimentation and deposition of a material with a highly porous, open structure with a high void ratio. Following isostatic uplift, the pore water chemistry of these materials may have been altered as a consequence of the change from a marine to a freshwater environment. Salt, which originally contributed to the bonding between the clay particles may, therefore, have been leached from these materials by ground water and percolating surface water. If sufficient leaching of salt from the soil pore water occurred, a highly sensitive or “quick” material may result. Some of the most densely inhabited regions of Norway, such as the areas around Oslo and Trondheim are located in potential quick clay areas and hence large efforts are being taken to map its occurrence and extent. The area under investigation in this study, Smørgrav, has a history of quick clay sliding, the most recent event occurring in 1984, and a number of other slide scars are visible in the area surrounding the site. The main objective of this study was to assess the use of a number of geophysical techniques for mapping quick clay deposits.

## Smørgrav

The Smørgrav test site is located approximately 65 km west of Oslo (Fig. 1a), just east of the town of Vestfossen. The test site is being used by the Norwegian Geotechnical Institute (NGI) for quick clay investigations. The site is divided into two distinct areas, approximately 250m apart (Fig. 1). The first area, to the east, was where most of the original work preformed by NGI, in addition to most of the work detailed in this study was located. Electromagnetic (EM-31), Electrical Resistivity Tomography (ERT) and seismic (Multichannel Analysis of Surface Waves (MASW) and Seismic Refraction) methods were tested in this area.  Area 2, to the west, is the site of the 1984 quick clay landslide. In this area only ERT and seismic profiles were acquired. This paper describes the preliminary findings from this study.

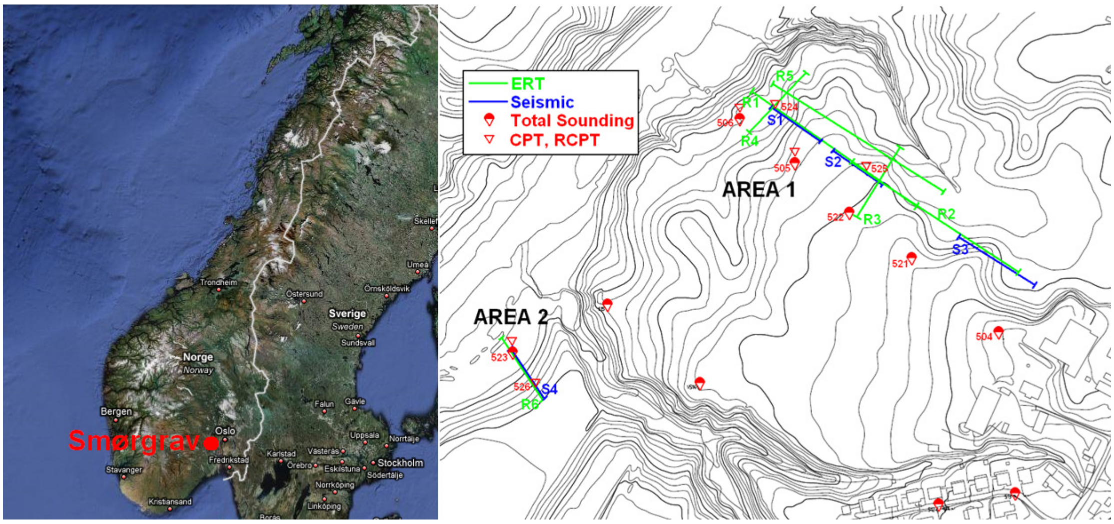


Figure 1: a) Location of Smørgrav test site (adapted from Google Earth TM mapping service), b) Site Map

## Electromagnetics (EM-31)

An electromagnetic survey, using an EM-31 electromagnetic induction meter was carried out in Area 1. Most of the survey was conducted in Northeast-Southwest lines, although a number of repeat readings were acquired in the Northwest section of Area 1. The results for the electromagnetic survey are shown in Figure 2 for the quadrature component of the electromagnetic field. It should be noted that EM-31 provides a measurement of conductivity within 6 m of the surface and therefore can only give an indication of the clay "outcropping" just below the dry-crust. As a result quick-clay layers below this depth may remain undetected. A gradational change in conductivity is observed, from Northwest to Southeast, with significantly higher conductivities (up to 80 mS/m) measured in the Northwest corner. This could possibly be interpreted as an increase in salinity, thereby indicating of the presence of an unleached or non-quick material. Electrical services (the location of which were known in advance of testing), were also detected using this approach and are observed on Figure 2 as a Northeast-Southwest trending anomaly.

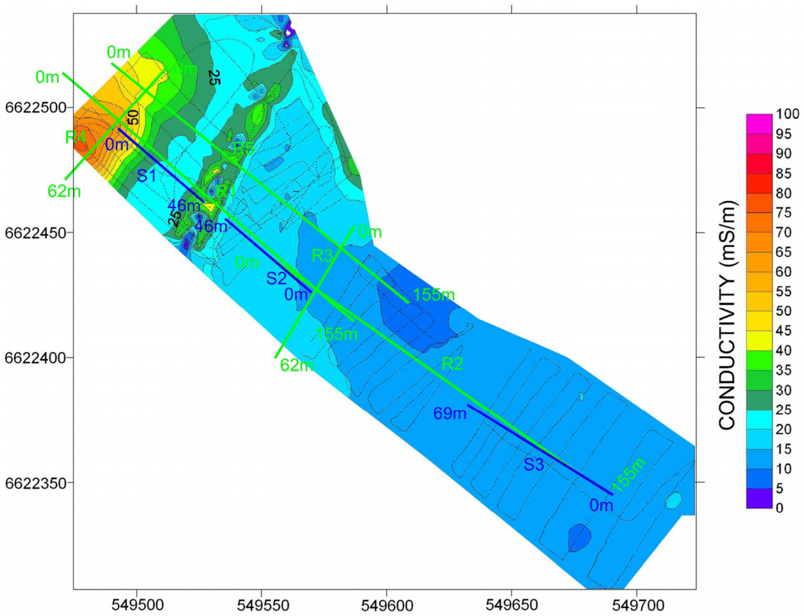


Figure 2: EM-31 survey results along with the corresponding locations of ERT and Seismic profile lines

**Electrical Resistivity Tomography (ERT)**

Two-dimensional (2D) electrical resistivity tomography surveys were performed along five profiles in Area 1 (R1 – R5) and one profile in Area 2 (R6, Fig. 1). Data was acquired using a multi-electrode Campus Tigre resistivity meter with a 32 takeout multicore cable and 32 conventional stainless steel electrodes. A four electrode Wenner array configuration was used to acquire multiple readings for each ERT profile. The results of ERT surveys R1, R2 and R6 are shown in Figure 3. As illustrated, there is a reasonably consistent upper layer of higher resistivity, approximately 2-3m thick, along the length of these profiles, which corresponds to the upper crust. Below this thin crustal layer in R1 and R2 there appears to be a gradational change in resistivity (similar to that observed in the EM data, above), with higher values (>100 Ωm) measured in the Southeast (uphill) and becoming very low (1 – 10 Ωm) in the Northwest (river end). According to the criterion of Solberg et al. (2008), resistivity values in the 10 – 80 Ωm range may indicate quick clay. This would therefore indicate that quick clay may be present in the area marked on Figure 3. Although Occam-style inversion models are generally ill suited for detecting discrete geological boundaries, in this case, however, a detailed analysis of borings and rotary pressure soundings indicate the highlighted contours as a likely interface between unleached and quick clay. The high resistivity values (>100 Ωm) detected in Profile R2 indicate shallow bedrock in this area, again confirmed by rotary pressure soundings.

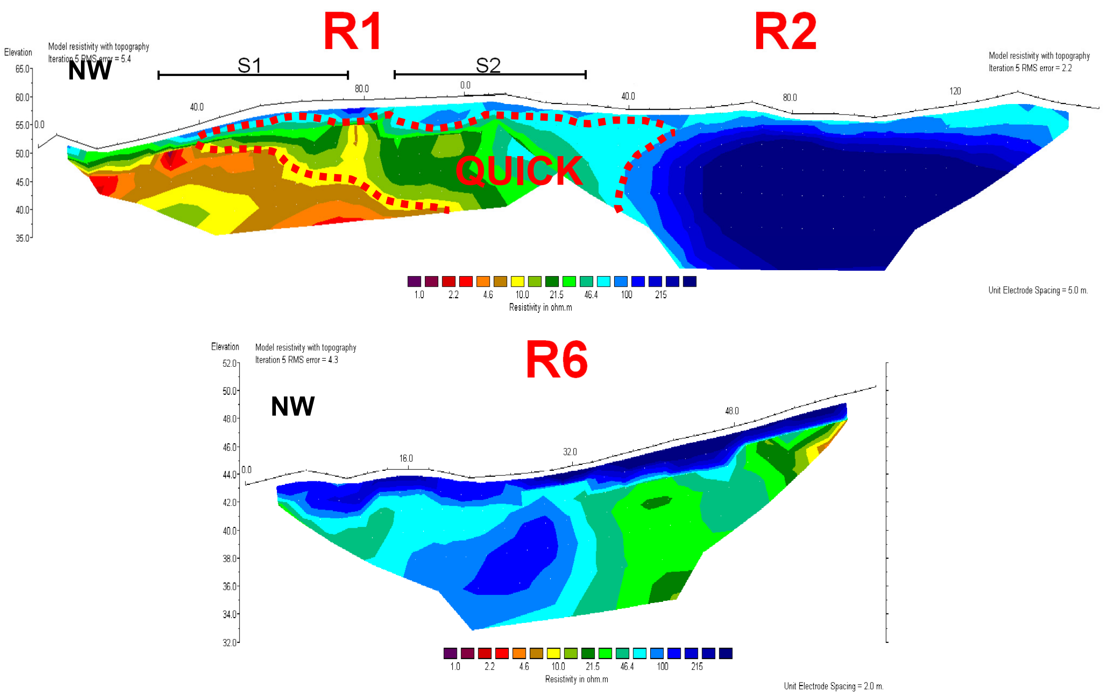


Figure 3: Electrical Resistivity Tomography results for Profiles R1, R2 (Area 1) and R6 (Area 2). Locations of seismic spreads S1 and S2 are also indicated.

The inverted resistivity profile for R6, at the location of the recent quick clay slide (Area 2), is also shown in Figure 3. As before, a high resistivity crust, of about 2 m thick is present across the length of the profile. Beneath this layer there is again a contrast between the inverted resistivity values to the NW and SE. In this case, however, part of the remoulded slide mass has been deposited in flat ground towards the NW. As shown the values for this material are high, generally greater than 40 Ωm. Interestingly, some of these values are in a similar range (although on the high end) to those expected for quick clay. To the Southeast (uphill) resistivities are generally in the 10 – 50 Ωm range below the crust, possibly indicative of quick clay.

### Multichannel Analysis of Surface Waves

The seismic data was recorded using a Geometrics Geode seismograph (with 24 geophones). A 10 kg sledgehammer was used to generate the surface waves which were in turn detected by 10Hz geophones. A number of different source locations were chosen for each MASW profile, to determine the optimum acquisition parameters, at a number of source-receiver offsets. Processing of the MASW data was performed using the software, Surfseis, which was used to select dispersion curves from a phase velocity-frequency spectra, generated using a wavefield transformation method (Park et al., 1999). 1-D shear wave velocity models were estimated by Surfseis using the Levenberg-Marquardt and single value decomposition inversion techniques detailed by Xia et al. (1999). Results for two of the MASW profiles, S1 and S2 (see Figure 1) are discussed here. Inverted shear wave velocity ($V_s$) profiles for these profiles are illustrated in Figure 4d. S1 is located over the region of low resistivity, possibly unleached material, whereas S2 is located over the zone where resistivity values were measured in the expected quick clay range (Figure 3). As shown, profile S1 exhibits higher inverted velocities down to a depth of 10m, with the greatest difference between the profiles observed between 2 and 5 m depth. At this depth the difference between profiles is as great as 17 m/s (137 m/s – 120 m/s), which corresponds to a difference in $G_{max}$ ($G_{max} = \rho . V_s^2$) of about 8 MPa. These differences should be examined further at other sites.

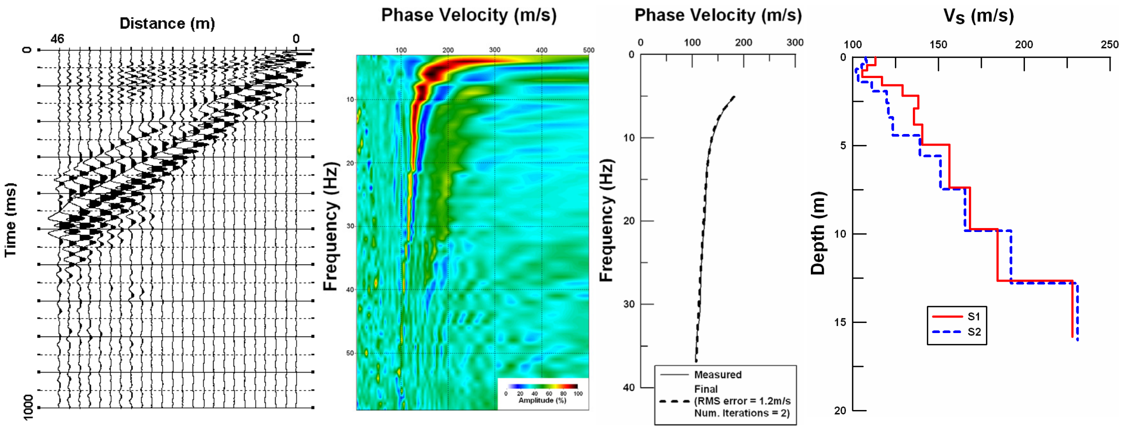


Figure 4: Processing of MASW data (a) Raw seismic data, (b) dispersion image for S1, (c) dispersion curves with estimated errors, (d) inverted $V_s$ profiles for S1 and S2

## Conclusions

The main objective of this work was to assess the use of a number of geophysical techniques for the identification of quick clay. A number of these approaches have proved very promising and it was found that:

- The EM-31 electromagnetic survey detected a gradational change in conductivity, with significantly higher conductivities measured in the Northwest area of the Smørgrav site, possibly corresponding to unleached marine clay.
- The Electrical Resistivity Tomography (ERT) approach proved to be the most successful of all the surface geophysical techniques. An extensive amount of clay with a resistivity of between 10 and 80 Ωm was observed on site, which appears to correspond to quick clay, the presence of which has been confirmed by both borings and rotary pressure soundings. Resistivity values for the remoulded slide mass are in a similar range (although on the high end) to those expected for quick clay. These values may also be indicative of silt or fine-grained boulder clay/ glacial till. This suggests that resistivity measurements should not be used as a stand alone tool for quick clay investigations, unless properly calibrated on a site to site basis using, for example, boreholes or rotary pressure soundings.
- Shear wave velocities for quick clay, measured using the MASW approach, appear to be slightly less (up to 15 – 20 m/s) than those measured for non quick clay. This difference warrants further study.

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