Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-443

High-resolution Geophysical mapping of the quick clays in Gjerdrum, Norway

S. Tavakoli[1], T. Le[2], A. Shulgin[3], L. Vikberg[4], S. Eskeland[5]

[1]*Senior Geophysicist, Norwegian Geotechnical Institute, Oslo, Norway, email: saman.tavakoli@ngi.no*

[2]*Senior Geotechnical Engineer, Norwegian Geotechnical Institute, Oslo, Norway, email: thi.le@ngi.no*

[3]*Senior Geophysicist, Geomap Norway, Oslo, Norway, email: alexey@geomap.no*

[4]*Senior Geophysicist, Geomap Norway, Oslo, Norway, email: lennart@geomap.no*

[5]*CEO, Eskeland Electronics, Ski, Norway, email: se@detektor.no*

ABSTRACT

About 5,000 km^2 of Norway is covered by marine deposits, with 20% of this area consisting of highly sensitive clay, or quick clay. Currently, over 110 000 people live in ca. 2300 quick clay zones in Norway. In the early hours of December 30th 2020 at Ask village in Gjerdrum, Norway, a quick clay landslide cost the lives of ten residents and led to substantial destruction to buildings, infrastructure and the environment in the region. To better understand the ground conditions, a combined geophysical-geotechnical investigation campaign took place at and around the landslide area in Gjerdrum in three zones. The following geophysical data were collected: (i) Electrical Resistivity Tomography (ERT) profiles in all three zones; some of which measured with multiple electrode configurations, (ii) ground-magnetic measurements in zones 1 and 3 covering three ERT profiles. Preliminary interpretations of the collected data provided useful insights into subsurface stratigraphy of the studied zones which helps indirect characterization of the quick clay and its associated structures. Layers of quick clay were identified using DC resistivity data with low resistivity values of ca. 20 – 120 Ωm. Bedrock in most of the profiles indicated high resistivity contrast compared to its covering till and quick clay layers. Wenner array data indicated higher resolution compared to Gradient array. Ground magnetic anomalies did not prove efficient for modelling of the pre-dominantly horizontal layering in the area; However, they were used as a constraint to other data including ERT results. Results from interpretations of the ERT data indicates three major stratigraphical units. A thin layer of dry crust with generally higher resistivity compared to the underlying (pre-dominantly) clay layer. Clay layers are distinctive with relatively low resistivities (below 150 Ωm). Bedrock is characterized with high resistivity values i.e., 600 to 1000 Ωm and depth to bedrock indicates large variations i.e., as shallow as 8 m down to 60 m depth.

ERT and magnetic data after processing will be constrained by the results from other geophysical data and geotechnical investigations to delineate the existing ground geo-model. These datasets, wherever overlap, can help to verify the interpretations.
Study results shows that appropriate choices of geophysical data can be effectively applied in combination with geotechnical investigation to map quick clays over large areas. This, when used in combination with other indirect interpretations e.g., depth to the top of bedrock, can provide significant information about ground conditions and thereby reduce the risks associated with quick clay landslide.

Keywords: Quick clay landslides, geophysical mapping, electromagnetic, resistivity, refraction seismic, geotechnical investigations

1 INTRODUCTION

The thickness of the clays in Gjerdrum were estimated based on available geotechnical investigations and shows variations across the area for different profiles. In some areas, clay layers extend from surface to 50m depth, of which the top 10-15 m constitutes clays and the lower 35-40 m is classified as quick clay (NVE Rapport, nr. 2/2021). These interpretations are based on a limited number of boreholes i.e., 58 boreholes in total drilled for different purposes by different companies (NVE Rapport, nr. 2/2021). Extrapolation between boreholes must be used to construct the ground condition in areas without boreholes. In addition, very limited information is available at depths below 50 m. According to the NVE Rapport (nr. 2/2021), damages in the building foundations were identified in several settlement areas in the Gjerdrum which could have been caused due to the lowering of the groundwater level. Only geotechnical sampling can, with certainty, detect or disprove layers of the quick clay. Although geotechnical investigations provide reliable results, information retrieved from them are limited to where boreholes are available. This is because the drilling, sampling and laboratory analysis of the samples are costly, time consuming and do not provide continuous results.

Geophysical methods can contribute to overcome the limitations in terms of time, data continuity and cost of geotechnical investigation in areas where quick clay present. Results from geophysical surveys can be used to constrain interpretation of the geotechnical field investigations. Information retrieved from geophysical investigations can, in addition, help to characterize other subsurface conditions e.g., locate the preferential leaching paths. Several geophysical methods including the ERT, and refraction seismic have been used previously in multiple studies in Norway and Sweden to characterize the properties of the quick clays (see e.g., Lundström et al. 2009; Bazin and Pfaffhuber, 2013). The previous geophysical studies of quick clay have had various successes and impacts, and they have explored important steps towards a non-intrusive complement to geotechnical testing. What makes this study more particular compared to many previous one is integration of the ERT and magnetic data in addition to geotechnical investigations and later constraining these interpretations with towed-Transient Electromagnetic (tTEM) and refraction seismic models. Therefore, there was a potential to improve resolution of the data and models, provide geophysical constrains, and also optimise efficiency in detecting quick clays with respect to associated costs and investigation times.

In this study, we aim to collect high-resolution geophysical data which will provide a basis for constructing a detailed 3D subsurface model. The proposed methods can characterise, with high resolution, parameters such as quick clay occurrences, depth to the bedrock and presence of a permeable layer above, below or embedded within the layer of quick clay (Talme, 1968). More specifically, our study aims to:

a) Compile ERT data at several sites around the landslide pit in Gjerdrum with high-resolution
b) Investigate the effect from electrode arrays on data resolution
c) Examine consistency in interpretations of the ERT and ground magnetic data
d) Study parameters which have indirect effect on the presence or localisation of the quick clays such as electrical and magnetic properties of the soil and bedrock and ground water level
e) Using high-resolution data, provide a basis to construct detailed 3D ground model of the site

Later, the results from this study will be incorporated with additional data including towed-Transient Electromagnetic (tTEM), refraction seismic and further geotechnical data to construct a high-resolution 3D model of the subsurface, as a part of the HIGELIG (High-resolution Geophysical mapping of the quick clays in Gjerdrum) project. Such well-constrained model will help to reduce uncertainties in the interpretation, which is an important basis to minimize the risk for future potential quick clay incidents in high-risk residential areas.

1.1 The study area

The Ask neighbourhood is the administrative centre of the Gjerdrum municipality and is located ca. 20 km north-east of Oslo (Figure 1). With a population of 6890 inhabitants as of 2020, the area has been subjected to the most recent major quick clay landslide in Norway. Historical and recent geotechnical data are available and accessible together with detailed technical reports, providing a good basis for planning and conducting the geophysical investigations accurately and to verify study results.

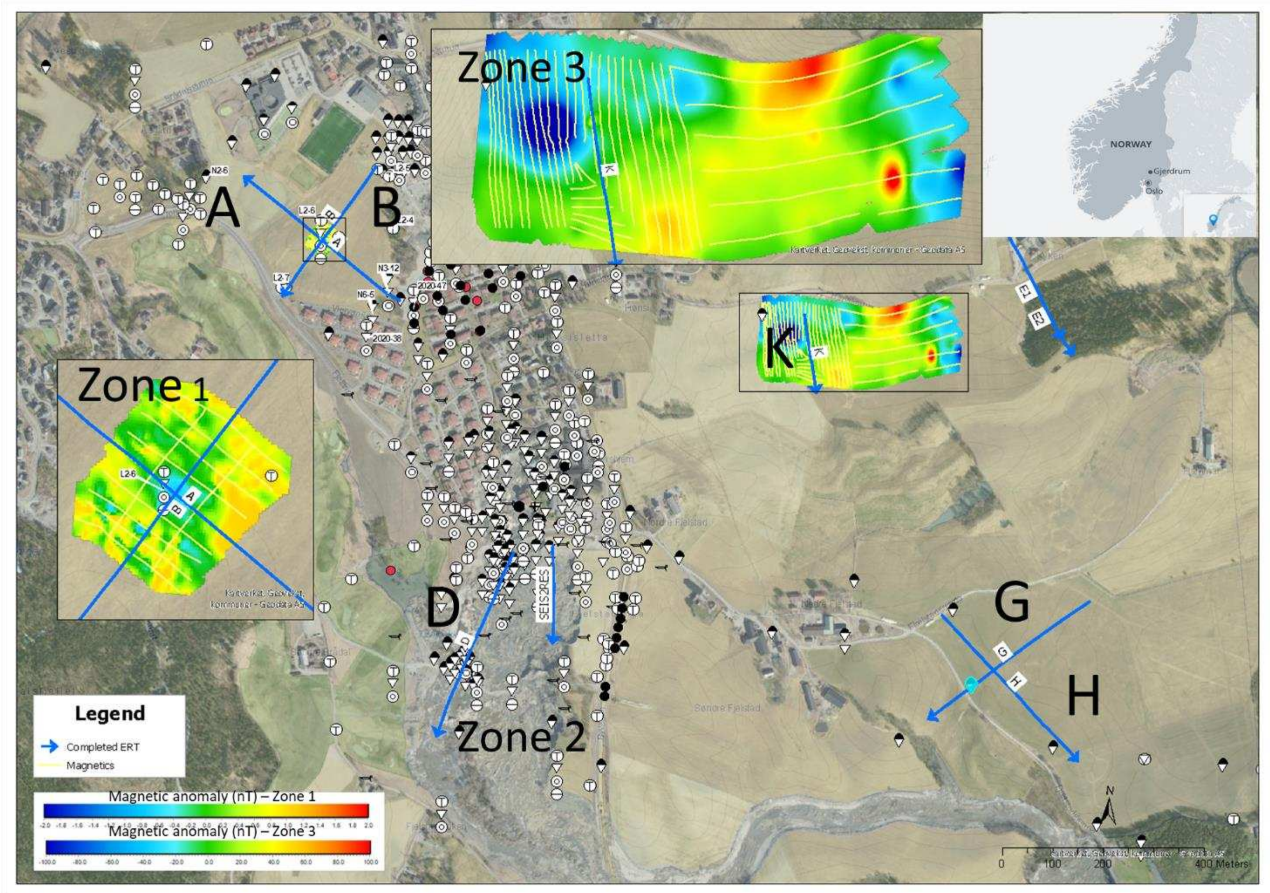

Figure 1. Overview map of the study zones for geophysical measurements. ERT profiles are indicated in Blue, magnetic lines in Yellow. Magnetic anomaly grids are enlarged and shown next to the survey area in each zone. Location of the site is indicated in the top-right corner.

2 METHODOLOGY, COLLECTED DATA, AND PROCESSING

2.1 DC Resistivity and Induced Polarization (ERT)

The ERT field work was conducted during early days of September 2022 and took 5 days to complete. Air temperature during the survey was variable between 6°C to 25 °C. Except for last two days of the fieldwork, which was mostly raining, the weather conditions was dry which made it suitable for homogenous injection of current into the ground.. Seven ERT profiles were measured in the study area to characterize zones which are susceptible to presence of quick clays (Figure 1). Two profiles were measured in zone 1, two profiles in zone 2, and three profiles in zone 3. Profile lengths were variable between 160 m to 400 m and electrode spacing was chosen between 2 m – 5 m to provide high vertical resolution of ca. 1 m to 2.5 m (Table 1). An ABEM LS2 Terrameter was used for ERT data acquisition with a spread of n × 21 electrodes, n denoting number of cables which was variable for each profile. The main electrode configuration used was Gradient-XL; However, data were also collected using the Wenner-alpha and dipole-dipole arrays. Additional details about the ERT profiles are given in Table 1.

Table 1. Seven measured ERT profiles. Electrode configurations and spacing, and coordinates are given.

Profile	Zone	Spacing (m)	Electrode array	Length (m)	X, Y Start	X, Y end
Profile A	1	5	Gradient	395	613134.6, 6660790.7	612803.1, 6661009.1
Profile B	1	4	Gradient	320	613063.4 6661052.8	612901.5, 6660778.5
Profile D	2	5	Gradient	400	613404.2, 6660315.3	613283.8, 6659937.7
Profile G	3	5	Gradient	400	614550.7, 6660322.4	614251.5, 6660060.0
Profile H	3	5	Gradient	400	614268.2, 6660260.5	614434.3, 6660112.7
Profile K	3	2	Dipole-dipole	160	613934.8, 6660838.0	613972.6, 6660683.1
Profile seis Z	2	5	Gradient, Wenner	200	613479.3, 6660337.3	613496.7, 6660141.4

Preliminary inversions of the seven ERT profiles A, B, D, G, H, K, and seis_Z were conducted using two different inversion codes Res2DINV and AarhusINV. However, final interpretations and presentations of the inverted profiles was made using the latter. Induced Polarization (IP) data, except for few profiles, indicated noisy and were therefore excluded from this paper. The main stratigraphical units from subsurface which are inferred from interpretations of the ERT data, are explained in section 3.1. Most of these interpretations, are consistent with other collected geophysical results.

2.2 Ground magnetic data

A ground magnetic survey was conducted in parts of zones 1 and 3 (see Figure 1) to check for possible magnetic anomaly signatures related to the subsurface stratigraphy units, in particular matching signatures related to depth to the magnetic bedrock with both ERT and magnetic data. We utilized a push-cart magnetometer system MAGNETO® MXPDA equipped with an optional RTK DGPS which allowed geo referenced measurements. The data and the measured tracks were displayed directly on the screen hence provided detailed surveys whenever an interesting anomaly presented. The instrument was equipped with 5x sensor channels and sampling rate was set to 100 Hz / 24 Bit. Sensor spacing was set to 0.25 m and the entire system was mounted on a pushcart (L X W X H) 1.4 m x 1.25 m x 0.9 m to facilitate moving the instrument. Processing of the magnetic data was conducted in Geosoft (Oasis Montaj). An upward continuation of 2 m was applied on the data to eliminate the near-surface unwanted anomalies including noise (Figure 2).

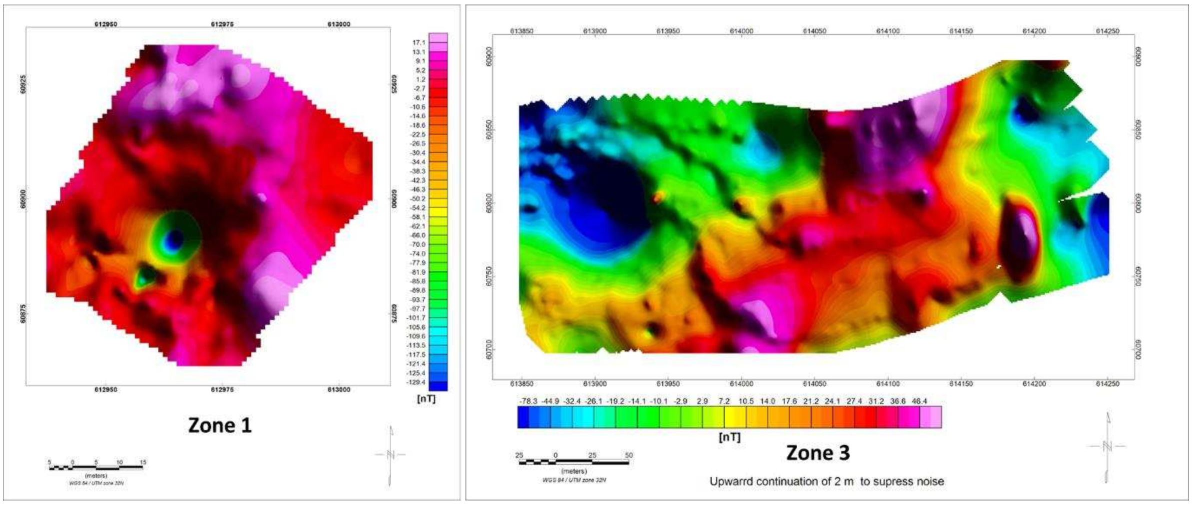

Figure 2. Vertical gradient of the magnetic field data in zone 1 and Zone 3 in Gjerdrum. 2 m upward continuation is applied on the data. The magnetic anomaly map is indicated using a slightly different value range and colour-code in shaded form to signify high magnetic anomalies. The absolute anomaly values are not of relevance here, rather relative magnetic anomaly variations is of interest.

3 RESULTS AND INTERPRETATIONS

The results in this study predominantly rely on interpretations of the ERT data. These interpretations are later checked against the overlapping parts of the profiles with magnetic anomaly map. In addition, results from this study will be integrated with tTEM and seismic interpretations which are currently being processed. The following three stratigraphy layers can be distinguished based on the ERT results: (i) topsoil, (ii) clay zones, and (iii) bedrock which are briefly explained below.

3.1 Results from ERT data

Topsoil (unsaturated soil)

A generally thin layer of soil can be identified from interpretations of the DC resistivity model sections. This layer shows higher resistivity compared to the underlying (pre-dominantly) clay layer. The relative high resistivity of this layer (ca. 200 – 400 Ωm) can be explained by its dry nature being unsaturated due to its placement above the ground water level.

Clay zones - Quick and non-quick

Several distinctive layers which are associated with relatively low resistivities (below 150 Ωm) can be observed within shallow parts of the subsurface stratigraphy in the inverted resistivity sections. These layers can be observed at depth as shallow as 5 m or at greater depths e.g., 20 m below the surface topography (Profiles A, B, D; Figure 3). Occurrences of quick clays along profile D is confirmed by results from geotechnical investigations. Moreover, resistivity values associated with parts of these profiles are slightly higher compared with overall observed resistivity of the Norwegian quick clays ranging between 10 to 100 Ωm (See e.g., Solberg et al. 2011). A similar low-resistivity zone is also observed in profile G which can potentially indicate quick clay; However, no borehole or geotechnical test results are available from this part to support this interpretation.

An alternative interpretation for the low-resistivity zone in profile G (Figure3) and for similar anomalies in the study area, if no geotechnical constrains are available, can be presence of porous layer which acts as fluid transport passage from upper levels to lower levels. Differentiation of the quick clay from non-quick clays requires a comprehensive study and laboratory test results. However, a couple of indirect geophysical anomaly indicators can give an insight to differentiate between the two types of clay. These indicators are, but not limited to: (i) higher expected resistivity of the quick clays compared to the non-quick clay as a result of lowered salt content for the quick clay, and (ii) being exposed to water drainages from the upper (porous) layer, (iii) placement on top of an undulating bedrock, which the latter seems to be the case for major parts of the study area based on the modelled bedrock inferred from resistivity interpretations.

Bedrock

Based on results from DC resistivity interpretations in this study, bedrock in the study area is characterized with high resistivity values i.e., 600 to 1000 Ωm (Figure 3). The depth to bedrock indicates large variations i.e., as shallow as 8 m down to 60 m depth. Along the measured profiles, the bedrock often indicates an undulating pattern (e.g., profiles G and H; Figure 3), providing an "ideal" condition for the formation of the quick clays (Rankka et al. 2004). The resistivity values within the bedrock indicates homogeneity, although minor fluctuations can be related to variations in formation porosity and water-filled fractures.

Profiles K and Seis indicate low resolutions in the inverted models and limited penetration depth; therefore, no interpretations were inferred from these two profiles.

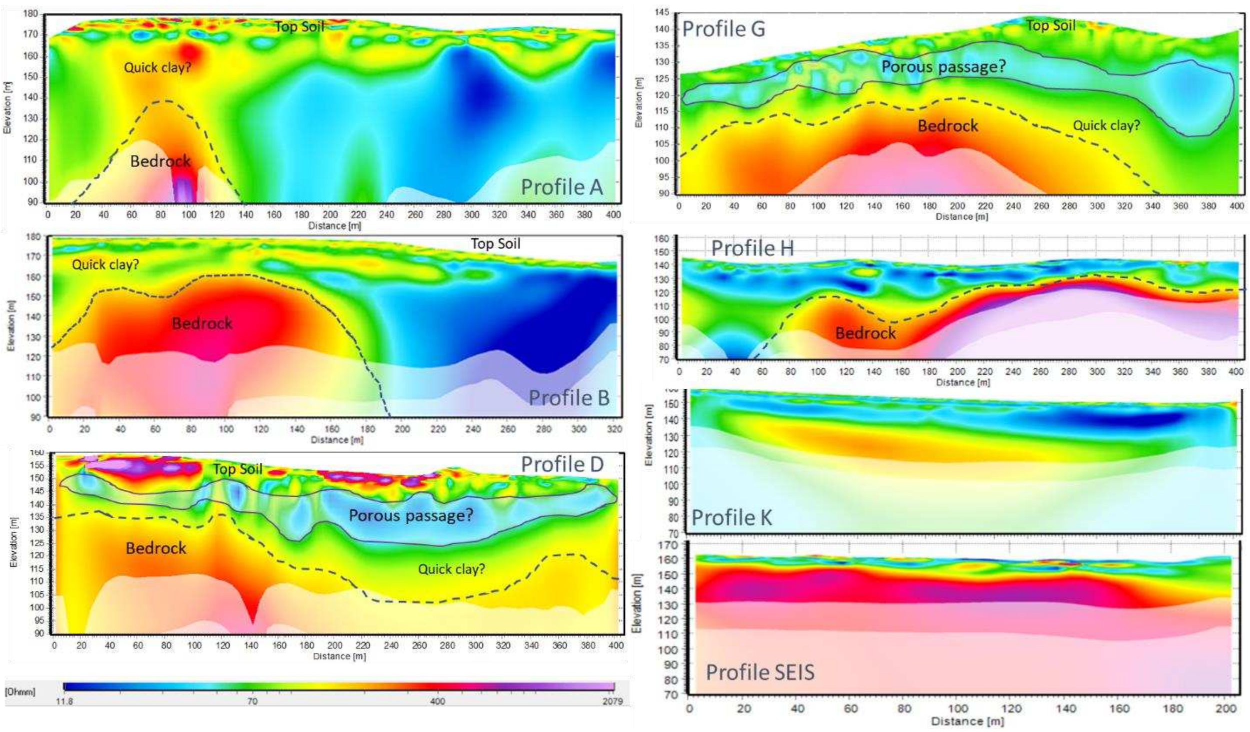

Figure 3. Inverted ERT profiles and preliminary interpretations for profiles A, B, D, G, H, K and Seis_z. Location of the ERT and magnetic profiles (this study) and also tTEM and refraction seismic profiles (parallel study) are indicated.

3.2 Magnetic data

Magnetic data are widely used to identify geological units with considerable contrast between magnetic susceptibilities, mostly for differentiating between vertical-laying sequences and hence are less efficient to identify horizontal layers. Considering the overall sub-horizontal stratigraphy of the area and also the small expected contrast between magnetic properties of these layers, no significant magnetic anomaly was expected. This can be observed e.g., in the anomaly map in Zone 1 (Figure 2). In Zone 3, an overall magnetic low anomaly in the NW of zone 3 can be recognized from a high magnetic anomaly in the rest of survey area. Considering that the bedrock was not imaged in profile K (the effective penetration depth is shallower than depth to bedrock), studying consistency between ERT and magnetic data is not possible. It is clear from both ERT and magnetic anomalies that the bedrock is not shallower than 30 m below the surface topography. Several peaks of magnetic highs in eastern areas of Zone 3 can be explained by shallower depth to the top pf the bedrock in those areas (Figure 2).

4 DISCUSSION

4.1 Consistency between measurements using different electrode configurations

Profile Seis_Z in zone 3 was measured using both Gradient and Wenner electrode configurations to compare the consistency between the two different configurations for the same profile. Wenner array indicates more realistic model with higher resolution because of (i) generally higher signal to noise ratio (S/N) and (ii) higher sensitivity to middle parts of the section. Although this was at a cost of nearly 3 times longer survey time compared to that of the Gradient array (Figure 4). The sides of the profile section, on the other hand, are expected to associate with more accurate results for the Gradient array (Figure 4), due to higher sensitivity for the Wenner array within those parts. Profile Seis_Z is associated with low number of data points, which is because of its short length and chosen electrode spacing. Therefore, the generated resistivity model from both configurations indicates generally lower resolution than most other measured profiles in this study.

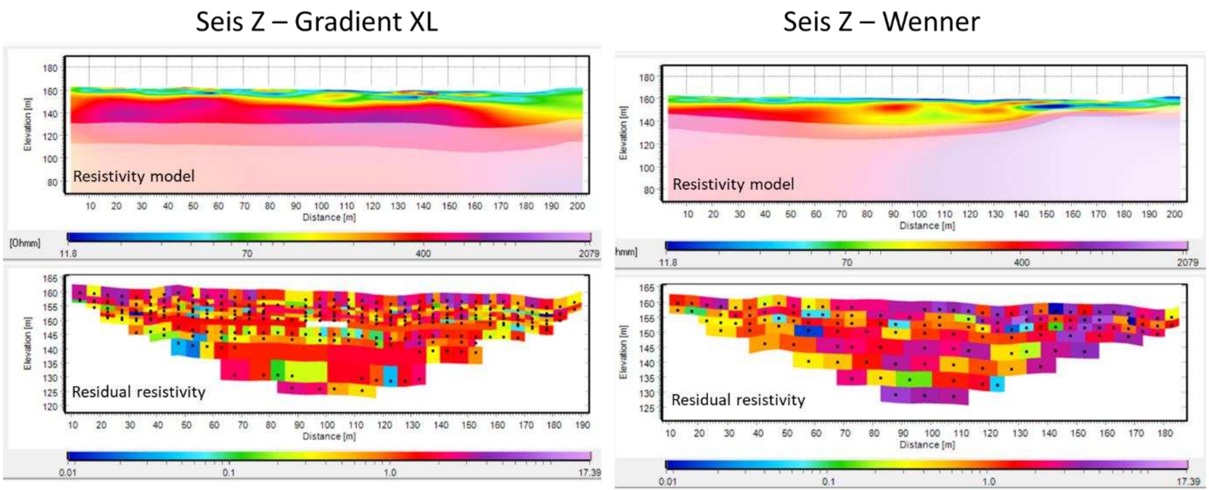

Figure 4. Comparison between Gradient XL and Wenner electrode configurations for profile Seis_Z. Upper model indicate the inverted resistivity model and lower section shows the residual resistivity data

4.2 Consistency between geotechnical data and ERT results

Profile D

Profile D was measured in NE-SW direction. Several geotechnical boreholes are located in close proximity (ca. 60 m or less) of the profile D. Interpretation of boreholes and resistivity models indicates a continuous layer of quick clay with thickness between 10 and 20 m (Figure 5). Beneath the quick clay layer lies a hard layer which probably represents bedrock or soil/moraine. As indicated in Figure 5, the low-resistivity area shown by blue coincides well with the layer interpreted as quick clay based on results from geotechnical investigations.

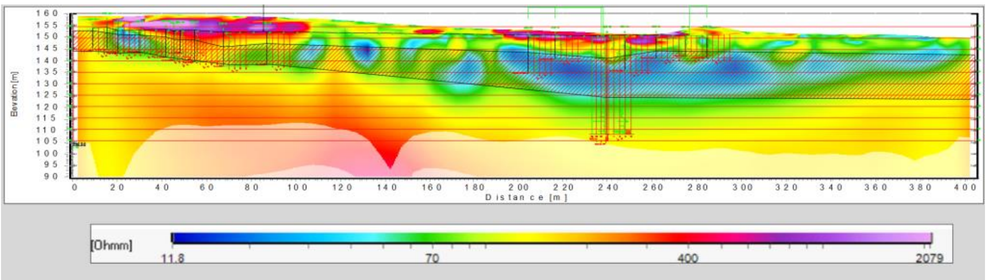

Figure 5. Interpretation of quick clay layer (hatched) along profile D in Zone 2

Profiles G and H

Only limited number of soundings are available along or near profiles G and H ((Figure 6 and Figure 7). The interpretation of quick clay layer bears therefore high uncertainty. There seems to be a continuous quick clay layer with 15 m thickness along these two profiles (Figure 6 and Figure 7). These interpretations agree well with the low-resistivity parts in these profiles which is interpreted as quick clay.

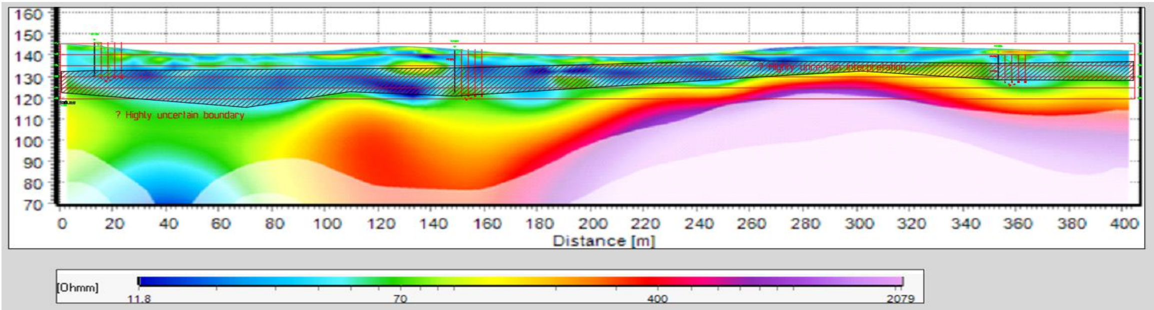

Figure 6. Interpretation of quick clay layer (hatched) along profile H

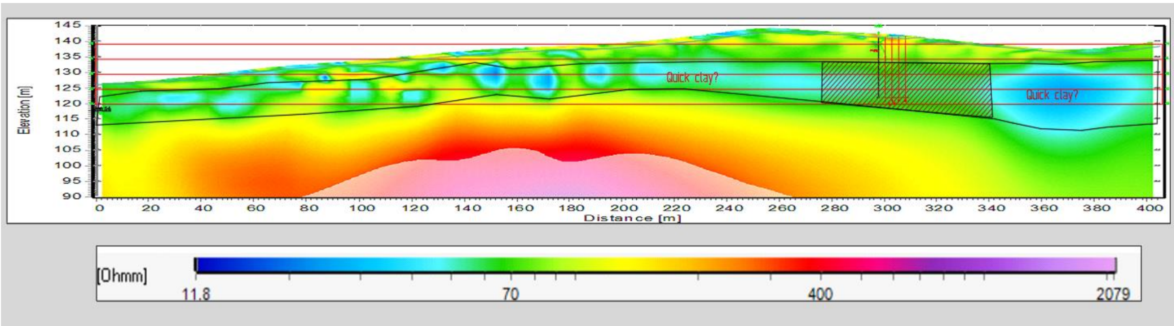

Figure 7. Interpretation of quick clay layer (hatched) along profile G

4.3 Correlation between magnetic and resistivity anomalies

The dominant (sub)horizontal layering of the subsurface stratigraphy signifies that no substantial magnetic anomaly can be expected from the near-surface features. However, the bedrock is expected to associate with considerably higher magnetic susceptibility compared to its overlying features I.e., clays and soil. Understanding the relationship between the features extracted from magnetic anomaly and resistivity data required forward and inverse modelling of the magnetic data and possibly joint inversion. However, since adequate processing was applied on magnetic data, graphical interpretations is possible to conclude. Three of the ERT profiles run within the measured magnetic data, profile A, B and K. The first two profiles only coincide with small parts of the magnetic anomaly, which homogenously indicate high magnetic signature. Therefore, no significant information can be extracted from this part. Profile K is almost entirely within the magnetic grid in zone 3 (Figure 2) and is associated almost entirely with low magnetic anomaly zone.

5 CONCLUSIONS

Preliminary interpretation of the ERT and magnetic data provided useful insights about subsurface stratigraphy of the studied zones which helps indirect characterization of the clay, quick clay, and its associated structures. These interpretations when constrained with other existing data provide an important basis for risk assessment for e.g., future construction planning and planning for possible stabilization measures. DC resistivity and magnetic data were compared to delineate the detailed stratigraphy of the subsurface. Information retrieved from interpretation of geophysical data were then checked against results from geotechnical investigations to further constrain the interpretations. Layers of quick clays were identified using DC resistivity data with low resistivity values of ca. 20 – 120 Ωm. These layers often underlie unsaturated and thin layers of soil. Understanding the vertical extension of the quick clay layers is not always possible due to loss of resolution at deeper parts and limited access to geotechnical test results. Nevertheless, bedrock was identified in most of the profiles due to high contrast between its resistivity and resistivity of the covering till and quick clay layers, both indicating lower resistivity compared to the bedrock. Wenner array data proved to provide overall higher resolution compared to Gradient array, but at the expense of higher cost due to longer survey time for the latter. The study results shows that DC resistivity data if measured with high-resolution and constrained with additional geophysical/geotechnical information, can provide significant insights about quick clays and their related structures. High-resolution and great investigation depth (up to ca. 100 m) achieved from ERT data when combined with complementary geophysical methods which can cover larger areas in shorter time (although with lower resolution) can be an efficient approach for early characterization of the quick-clay areas before landslides occur. The optimal goal of this study is therefore to integrate interpretations from multidisciplinary data for detailed risk assessment and to construct high-resolution 3D ground model of the study area. The developed methodology and outcome of this study can be used for early-stage site characterizations in similar geological environments in Norway and other countries where quick-clay presents.

6 ACKNOWLEDGEMENTS

This work is a part of the HIGELIG (project number 332792) - *High-resolution Geophysical mapping of the quick clays in Gjerdrum* financed by RFF-Viken. Norwegian Geotechnical Institute (NGI) and project partners i.e., Geomap Norway, Eskeland Electronics, Aarhus Geoinstruments and Viken fylkesKommune, are thanked for contribution in funding and involvements in field work and data processing. The project is partly funded by the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 101006512 through transnational access project QC-CEM.

REFERENCES

Bazin, S., Pfaffhuber, A. A. (2013). Mapping of quick clay by electrical resistivity tomography under structural constraint. J. Appl. Geophys. 98, 280–287. https://doi.org/10.1016/J.JAPPGEO.2013.09.002

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

Lundström, K., Larsson, R., & Dahlin, T. (2009). Mapping of quick clay formations using geotechnical and geophysical methods. Landslides, 6(1), 1–15.

NVE Rapport, nr. 2/2021 2021. Geoteknisk vurdering av evakuerte delområder etter kvikkleireskredet i Gjerdrum, 30.12.2020. ISBN 978-82-410-2107-7

Oasis Montaj. Available at [https://www.seequent.com/products-solutions/geosoft-oasis-montaj/]

Rankka K, Andersson-Sköld Y, Hultén C, Larsson R, Leroux V, Dahlin T. (2004). Quick clay in Sweden. Linköping: Statens geotekniska institut; (SGI Rapport).

Solberg, I.L., Hansen, L., Rønning, J.S., Haugen, E., Dalseg, E., Tønnesen, J.F. (2011). Combined geophysical and geotechnical approach to ground investigations and hazard zonation of a quick clay area, Mid Norway. Bull. Eng. Geol. Environ., 71, 119-133.

Talme, O. (1968). Clay sensitivity and chemical stabilisation. Byggforskningsradet, Rapport 56. Stockholm.