

Quick-clay Investigation using Radio-Magnetotelluric Method

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SUMMARY

Recent years have seen a significant rise in quick-clay landslides in Nordic countries, notably in Alta, Gjerdrum, and Stenungsund, causing severe damage and fatalities. This study explores the use of geophysical methods, particularly the radio-magnetotelluric (RMT) technique, to analyze quick clay characteristics and behavior in these regions. The RMT method offers an advanced approach to investigating the electrical resistivity of subsurface structures, vital for identifying quick clay zones.

The Rissa region in Norway serves as a focal point due to its historical quick-clay landslide and existing geophysical infrastructure. Following the devastating Rissa landslide in 1978, Norway initiated a comprehensive national quick clay mapping project, which this study builds upon. We also collected distributed acoustic sensing (DAS) data at Rissa, aiming to combine the two datasets for a thorough analysis.

Geological investigations at Rissa indicate a straightforward stratigraphy with flat terrain and a 20-meter-thick marine clay layer. Quick clay layers, distinguished by their higher electrical resistivity compared to marine clays, are found within borehole samples. The study employs RMT to map these layers and examine the influence of seasonal variations on their properties. RMT data were collected along a 250-meter RMT profile with 10-meter station spacing using the Enviro_MT instrument in both summer and winter.

Results reveal a four-layered model: unconsolidated sediment, marine clays, potential quick clays, and bedrock. Notably, seasonal variations affected resistivity models, with the marine clay layer appearing thicker in winter due to reduced freshwater, and potential quick clay pockets showing increased thickness in some areas. These findings demonstrate the effectiveness of RMT data in identifying resistivity changes at quick-clay sites due to seasonal variations. The velocity model inverted from DAS data indicates an increase in velocity with depth. However, it is hard to distinguish quick clays from marine clays in the velocity model. This research provides valuable insights into the dynamic distribution of quick clays and their seasonal behavior, with implications for infrastructure planning and disaster management in landslide-prone areas. The integration of RMT and DAS results offers a new perspective on studying and monitoring quick-clay landslides.

Keywords: Radio-magnetotelluric, quick clays, resistivity, seasonal variation

INTRODUCTION

During 2020, two significant quick-clay landslides were recorded in the Alta and Gjerdrum regions of Norway, followed by another in Stenungsund, north of Gothenburg in Sweden in 2023. These events resulted in substantial damages, impacting residential structures and infrastructure. Notably, the landslide in Gjerdrum was particularly tragic,

resulting in ten casualties. Research indicates a rising trend in the occurrence of quick-clay landslides over recent decades, a phenomenon potentially linked to climatic or seasonal changes (Cloutier et al., 2016; Danilov, 2021). Despite this, the precise relationship between escalating quick-clay landslide incidences and climate change remains insufficiently explored. Current research efforts are increasingly focusing on in-depth

analyses of quick clays, which could elucidate the potential correlation with at least seasonal change. Geophysical methodologies have been recognized in multiple studies as particularly effective tools for the investigation of quick clay regions. (e.g., Malehmir *et al.*; 2013, Wang *et al.*, 2016).

The radio-magnetotelluric (RMT) method, a branch of electromagnetic (EM) techniques, is employed to analyze the electrical resistivity characteristics of subsurface structures. This method utilizes radio-station transmitters to produce EM signals with a passive way (Bastani, 2001). RMT has gained widespread application in various near-surface studies, including the investigation of quick clay (Wang *et al.*, 2016), groundwater assessment (Yogeshwar *et al.*, 2012), and fracture zone delineation (Wang *et al.*, 2019). Research indicates that quick clay exhibits higher electrical resistivity compared to marine clay, attributed to the leaching process induced by low-salinity water. Consequently, the use of RMT data is considered effective for direct mapping of quick clays and permafrost in Nordic regions.

Located approximately 50 kilometers from the Norwegian University of Science and Technology (NTNU), Rissa presents an ideal site for conducting quick clay research utilizing RMT method, with NTNU serving as the operational base. The Rissa quick clay landslide of 1978, thoroughly documented by the Norwegian Geotechnical Institute (NGI), spurred a comprehensive national quick clay mapping initiative. This historical context offers a unique platform for advancing and evaluating novel techniques and concepts in quick clay modeling. Such research outcomes are invaluable, particularly for infrastructure planning in regions with quick clay presence. Our research team has also undertaken the collection of distributed acoustic sensing (DAS) data in Rissa, aiming to integrate DAS and RMT with quick clay studies and assess the multi-geophysical approach (as shown in Fig. 1). The proposed electromagnetic (EM) profile is designed to align with one of the existing DAS profiles. Opting for a RMT profile that crosses a borehole is strategic for calibration purposes (Fig. 1). This arrangement ensures a robust comparative framework between DAS and RMT results. More critically, this deliberate design approach is set to yield comprehensive insights into the quick clay and its surrounding environment at the Rissa site, encompassing resistivity, velocity, and other physical properties.

GEOLOGICAL INFORMATION

The Rissa quick clay site is characterized by a relatively simple stratification. The terrain is predominantly flat. Analysis of borehole data (W1 and W2, as indicated in Fig. 1) reveals that the marine clay stratum is approximately 20 meters thick, flanked by a slender soil layer (around 10 cm) and underlying bedrock. Notably, quick clay is sandwiched in the borehole samples.

At this site, layers with relatively higher resistivity could signify potential quick clays, as their formation involves salt leaching from pore water, and lower salinity correlates with increased resistivity. Furthermore, the resistivity profiles of unfrozen and frozen quick clay layers may differ significantly. Therefore, conducting RMT and other EM fieldwork during both summer and winter is crucial for studying the resistivity differences caused by seasonal variation. A time-lapse study could be instrumental in exploring the viability of monitoring quick clay dynamics using electromagnetic methods across varying seasons. Such investigations are expected to provide insights into the relationship between quick-clay characteristics, landslide occurrences, and climatic or seasonal variations.

METHOD

The RMT profile is about 250 m long with a station spacing of 10 m (Fig. 1). The instrument is the Enviro_MT from Uppsala University (Bastani, 2001). The first RMT data acquisition was carried out in July in 2022. The second acquisition was carried out in January in 2023. The purpose is to study the site characterization with RMT data in different seasons and compare the resistivity model inverted from the data with the velocity model inverted from DAS data. This experiment design can better constrain quick clays features in different seasons with complemented information from different datasets. Worth to mention that the controlled-source RMT data were also collection in the first fieldwork, but the repetition of controlled-source data collection was failed due to cold weather.

RESULTS

Inversion of RMT data is carried out by using EMILIA (Kalscheuer *et al.* 2008; Wang *et al.* 2016). The error floor is 5% on the impedance of RMT data. A 100 ohm-m half-space model is used as an initial model for all inversions. Two steps damped Occam approach is applied in all inversions. Firstly, we performed an Occam inversion with a regular smoothness constraint (Constable *et al.* 1987) with a variable Lagrange regularization parameter. Secondly, the best inversion model from step one

was then used as a new initial model in a damping Occam inversion with the Lagrange regularization parameter giving the best model in the first step.

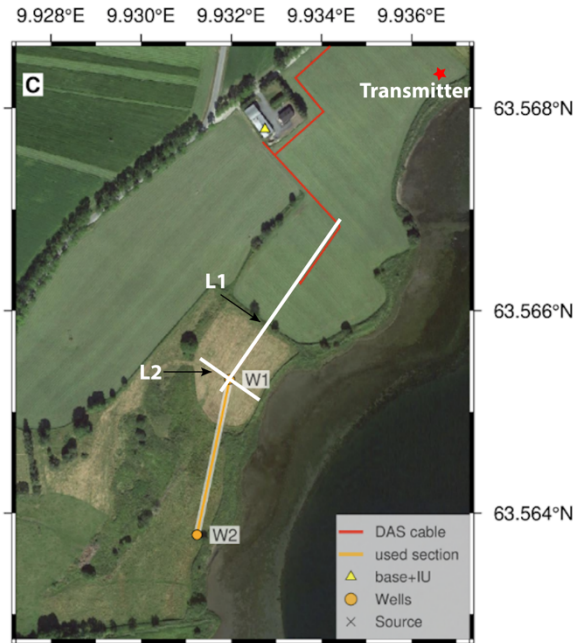


Figure 1. Survey lines in the field (after Rørstadbotnen *et al.*, 2023). Red lines represent the DAS cables, and white lines are the selected profiles, L1 and L2, for RMT or CSRMT surveys. CSRMT data were only collected in the summertime along L1, and only RMT data were collected along L2 in the wintertime. W1 and W2 are two bores used to study the quick clays at a laboratory. Our proposed profile L1 overlaps with part of the DAS line and cross W1 to fully utilize the borehole information. The transmitter is marked as a red star at the other side of the profile.

For the comparison purpose, the same parameters are used to invert both the summer and winter RMT data along L1, and L1 is chosen due to data availability. The inversions were done with TE-mode, TM-mode, and determinant data separately or in a combination. However, similar layering structures are shown in all inversions. Therefore, only the results of determinant inversions are shown (Fig. 2). In general, a four-layer model is resolved both from summer and winter data (Fig. 2). The four layers include an unconsolidated sediment layer at the surface, followed by a marine clay layer and a potential quick clay layer, then all three layers sitting on top of the bedrock. Seasonal differences can be observed through the resistivity models inverted from different datasets (Fig. 2). The marine clay layer is thicker in winter in general (Fig. 2). However, at some locations, the potential quick clays become

thicker. The results clearly show that RMT data can distinguish the resistivity differences at a quick-clay site due to seasonal variation related to temperature and fresh water.

The velocity model developed from surface wave tomography using DAS data indicates an increase in velocity with depth (black line in Fig. 2b, available from Rørstadbotnen *et al.*, 2023). This is compatible with resistivity model. However, we cannot identify where quick clays distribute in the velocity model, which is feasible in the resistivity model.

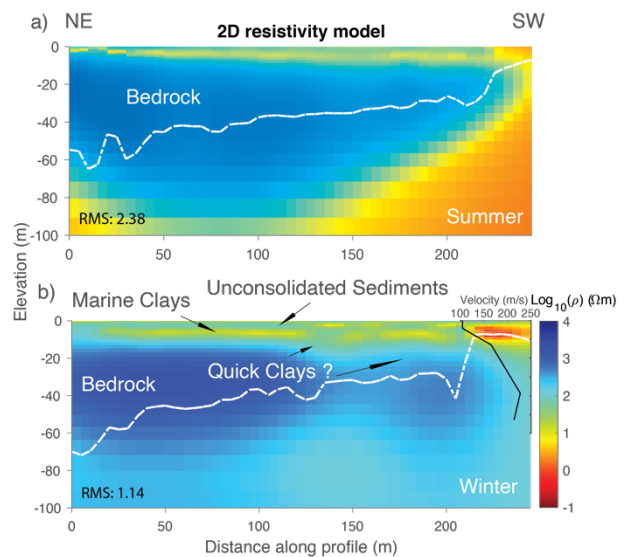


Figure 2. Resistivity models inverted from RMT determinant data a) collected in summertime and b) collected in wintertime. White dashed line presents the penetration depth of RMT data. Black curve shows the velocity model from surface wave tomography (Rørstadbotnen *et al.* 2023). The RMS of the inversion in (a) is 2.38, and the RMS of the inversion in (b) is 1.14. Each model fits the corresponding datasets best.

CONCLUSIONS

This study has demonstrated the efficacy of the radio-magnetotelluric (RMT) technique in investigating the characteristics and dynamic distributions of quick clay in Nordic regions. By integrating RMT with distributed acoustic sensing (DAS) data, we have successfully identified the electrical resistivity profiles of subsurface structures, crucial for locating quick clay zones. Fieldwork conducted at the Rissa site, with its distinct geological contexts, provided a robust dataset for our analysis.

The RMT data revealed a four-layer model: unconsolidated sediments, marine clay, potential quick clay, and bedrock. Seasonal variations

significantly influenced the resistivity measurements, with marine clays appearing thicker in winter due to the frozen ground condition. The quick clay layers exhibited increased thickness in some locations during winter.

These results underscore the potential of RMT for distinguishing resistivity differences in quick clay sites due to seasonal changes, offering critical insights for monitoring potential quick-clay landslides. The integration of RMT and DAS data represents a novel approach, enhancing our understanding of quick clays. The findings have significant implications for infrastructure planning and disaster management, providing a foundation for mitigating the risks associated with quick-clay landslides in affected regions.

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