Electrical Resistivity Tomography to follow up an airborne EM rock slide mapping survey – Linking rock quality with resistivity.

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Abstract

We investigate an active rock slide in Western Norway with ground- and airborne resistivity mapping to ultimately find weakness zones & sliding planes embedded in crystalline bedrock. The study area comprises phyllite, a low grade metamorphic rock type that tends to be reworked to clay in disturbed zones. Mapping these electrically conductive clay zones was the aim of the survey. GPS measurements over the last 5 years indicate that precipitation drives rock slide movements. The role of ground water is thus a crucial factor to investigate for risk assessment in the area.

Based on a successful airborne electromagnetic (AEM) demonstration survey, we conducted a total of 1.600 profile meters of ground resistivity measurements to confirm AEM anomalies, to gain precise 2D geometries and to link conductivity anomalies with geology.

All resistivity results confirm AEM anomalies and refine their lateral extent. In the East we find consistency between a strong conductor, dipping sub horizontal SW with an outcropping thrust fault, separating phyllite and gneiss. In the West a conductor dipping steeply NNW seems to be fed by surface water and may represent a formerly unknown sliding plane. Detailed geotechnical follow up is pending (drilling and instrumentation).

Introduction

The inner Aurland fjord and the adjacent Flåm valley (Western Norway) are one of Norway's most famous tourist destinations with up to 450.000 visitors and more than 100 cruise ships a year. Further, the main road between Oslo and Bergen (E16) passes through Flåm, bypasses the fjord and enters the 24.5 km long Lærdal-tunnel in Aurlandsvangen. Large rockslides in the geological past have been documented in the area and ground movements are evident to the present day. The area is subject to potential rockslides comprised of creeping rock and debris masses (Figure 1). With our study we intend to provide geophysical input to the ongoing natural hazard assessment in Aurland municipality.

From repeated GPS measurements and anecdotal observations in the area we understand that rock and debris movements are constrained by precipitation and snow melt. Based on this assumption the local municipality and regional hydroelectric company E-CO Vannkraft are evaluating the option to drain the unstable area with a 10 km long drainage tunnel to a nearby hydropower reservoir (Viddalsmagasinet). Here we discuss first interpretations from an airborne electromagnetic (AEM) mapping survey conducted in 2009 and a follow up Electrical Resistivity Tomography (ERT) campaign in 2010 to find indications of the sliding planes and to assess the tunnel corridor for potential tunneling hazard areas

Geology

The investigated area consists of a basement of Precambrian high grade metamorphic gneisses overlain by a nappe (sheet) of phyllite and another layer of high grade metamorphic gneisses with minor layers of quartzite and other rock types resting upon the phyllite layer. During the formation of the nappe the weaker phyllite acted as lubrication in the trust zone between the basement of precambrian gneisses and the overlaying gneisses. Normally the trust zone has recrystallized to a schistose layer, during the later low grade metamorphism.

Tunnel projects in the area have crossed these geological units and weakness zones where found frequently at the phyllite / gneiss interface.

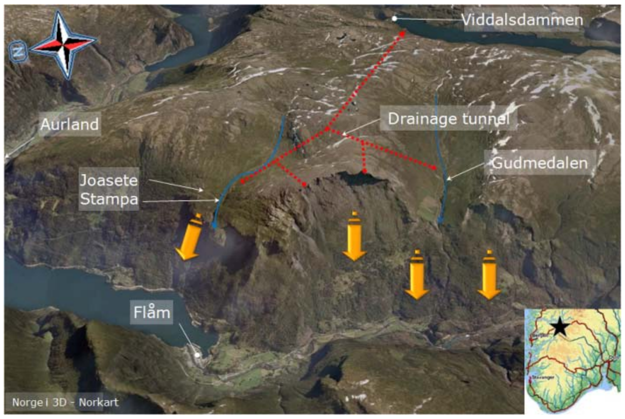

***Fig. 1** - Study area (aerial photography draped over topographic model courtesy of www.norgei3d.no) indicating areas with known previous rockslides and creeping movements (orange arrows) of both massive rock (fjord) and loose debris (valley) partly driven by pore water delivered by the Stampa and Gudmedalen catchments. Red lines indicate the potential water drainage tunnel system.*

Mapping strategy

Unstable rock in the study area some 1.000 meters above sea level has been mapped as massive phyllite intercepted by numerous tension cracks opening up to several meters (Figure 6). Field observations also point out that significant amounts of surface water in streams on the mountain plateau around Joasete disappear in some of these cracks and reappear on the surface several hundred meters down the slope. Potentially sliding planes provide the water pathways and the changes in water pressure can cause instability. As the phyllite may be crushed to fine grained clay the water saturated sliding planes should be an ideal target for AEM since they are very conductive (1-10 Ωm) in comparison to the resistive undisturbed phyllite or nearby gneiss (> 1.000 Ωm). Earlier ground resistivity measurements in the area, strengthen this hypothesis. Note that these geological conditions are in strong contrast to other Norwegian rock slides, like Åknes which is situated in gneiss with resistivities of several 1.000 to 10.000 Ωm even in the water saturated zones (Heincke et al. 2010).

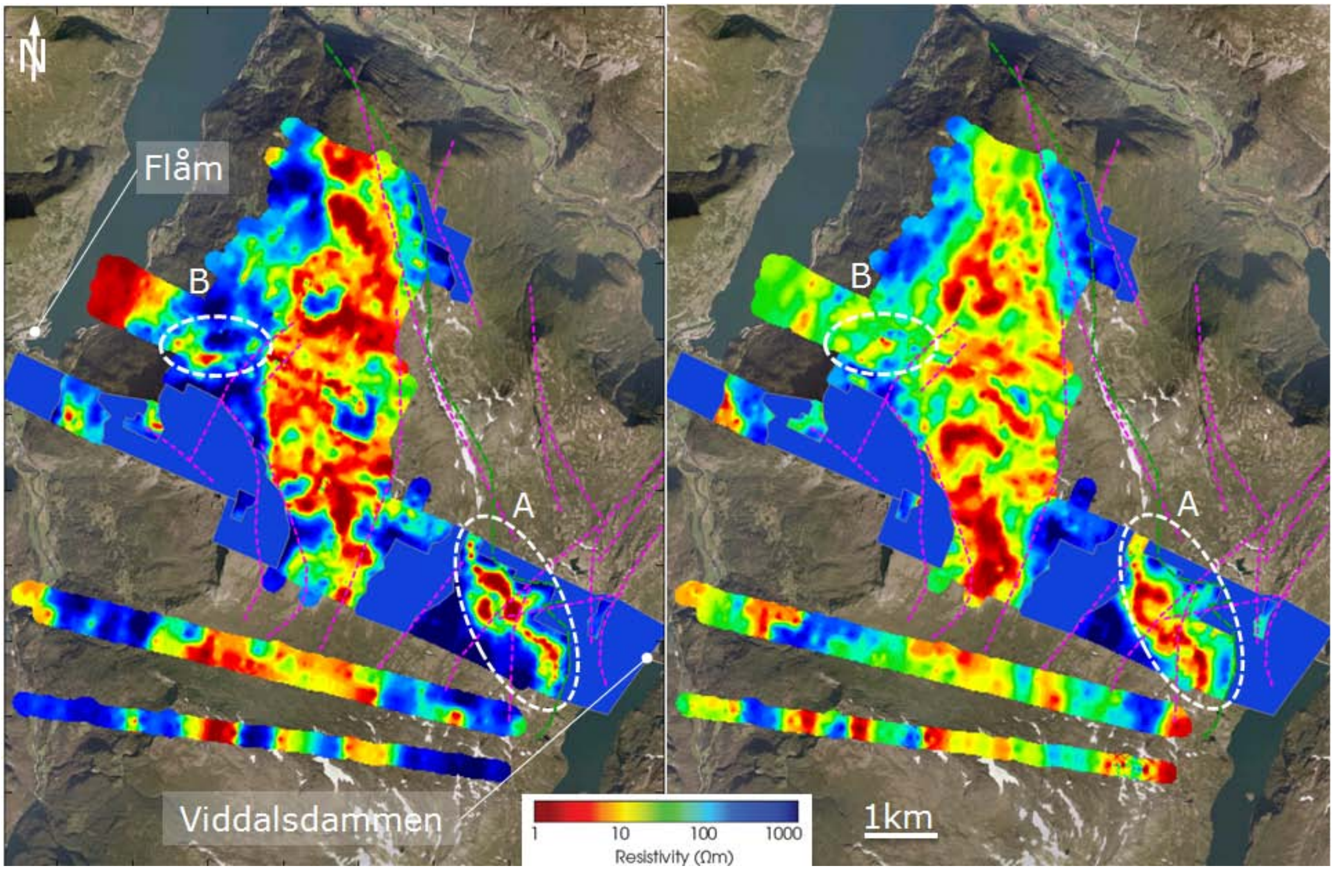

Fig. 2 - *Spatially constrained inversion (SCI) result: interval resistivity averaged from 40 m to 50 m (left panel) and 100 m to 110 m (right panel) below ground (depth slice) mapped over survey area. Purple and green lines roughly outline mapped weakness zones and phyllite/gneiss interface, respectively. Bright blue areas are areas where minimal AEM signal was be recorded due to highly resistive ground.*

AEM survey

The AEM survey was carried out with a helicopter borne, time domain EM system, SkyTEM (Sørensen and Auken, 2004). A total of ~250 line km where flown in three days at 125 m line spacing with some fill-in lines in the central part of the survey area. Standard processing and spatially constrained inversion, SCI (Viezzoli et al. 2008) were applied to the data resulting in resistivity maps and profiles indicating penetration depths up to 250 m. Pfaffhuber et al. (2010) provide further details on the AEM survey.

From our first AEM data interpretation we find widespread areas with high conductivity (shown as red in Figure 2), which are most likely caused by either water saturated, fine grained sliding planes or fault zones at the phyllite / gneiss interface. From our initial survey concept, we expected limited signals from phyllite reworked to clay but no significant response from the undisturbed phyllite and gneiss environments. Very much to our surprise, we found strong and consistent signals covering nearly the complete survey area. In the following we highlight two areas that were followed up by ERT surveys. For a discussion of other dominant AEM features please refer to Pfaffhuber et al. (2011).

- Lineament in the SE

A meandering distinct conductor close to Viddalsdammen roughly coincides with the phyllite / gneiss boundary known from surface mapping (Area A, Figure 2). Following the feature through different depth slices indicates a fairly flat dip towards SW (Figure 3) consistent with outcrop data. This is an indication for crushed phyllite and poses a formerly unknown potential hazard for a future tunnel.

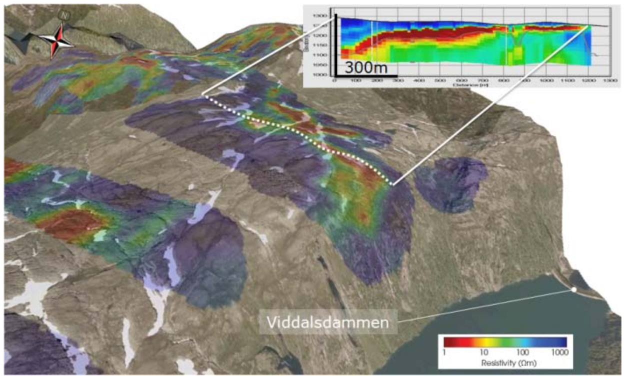

***Fig. 3 -** 3D visualization of area A adjacent to Viddalsdammen (Figure 2). The 30-40 m resistivity depth slice is draped 35 m below the topography. A conductivity depth section derived from SCI results following the green stippled line is also displayed..*

- Anomalies along the slopes

The subsurface around Joasete but also along the slopes down to Aurland fjord and Flåm valley features widespread conductive anomalies (Figure 4). The debris covered slopes usually feature consistent, thin conductors while the anomalies at Joasete and Stampa (Area B, Figure 2) are more complex, most likely caused by sub vertical 3D structures. The consistent, thin, conductive layer most likely indicates the base of debris filled with fines and thus the sliding plane for the creeping debris along the fjord and valley.

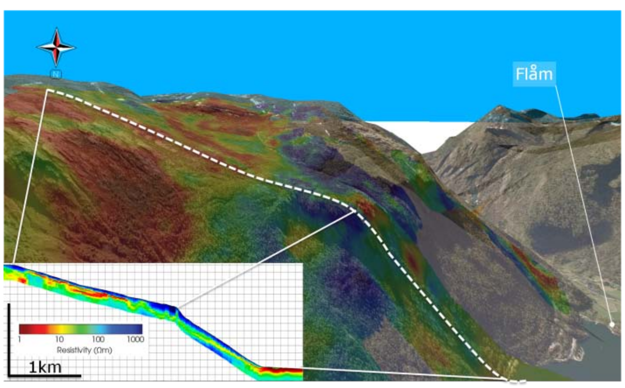

***Fig. 4 -** 3D visualization of area B around Joasete (Figure 2). A slightly transparent aerial photo is draped over topography with no vertical exaggeration. The 70-80 m resistivity depth slice draped 75 m below the topography shines through the aerial photo. A conductivity depth section derived from SCI results following the green stippled line is also displayed.*

Both cases indicate 3D or at least 2D geology and thus scratch the limit even of advanced AEM processing & inversion. The SCI algorithm is usually reliable for structures dipping less than 30 degrees. Consequently, we planned an ERT survey for detailed follow up of the AEM anomalies.

ERT survey

The ERT survey was carried out with a 12-channel *Terrameter LS* system (ABEM 2010). The unit was hooked up to four 100m long multi-electrode cables resulting in maximum a maximum spread length of 400 m at 5 m electrode spacing. We simultaneously acquired resistivity and induced polarization data sampling the potentials at 10 electrodes in parallel. Resistivity readings where integrated over 0.4 s with 0.2 s delay after turn on. For the IP measurements, the voltage decay was measured in 4 time-windows of 20 ms each, starting 10 ms after current turn-off. Minimum current injected to the ground was set to 1 mA.

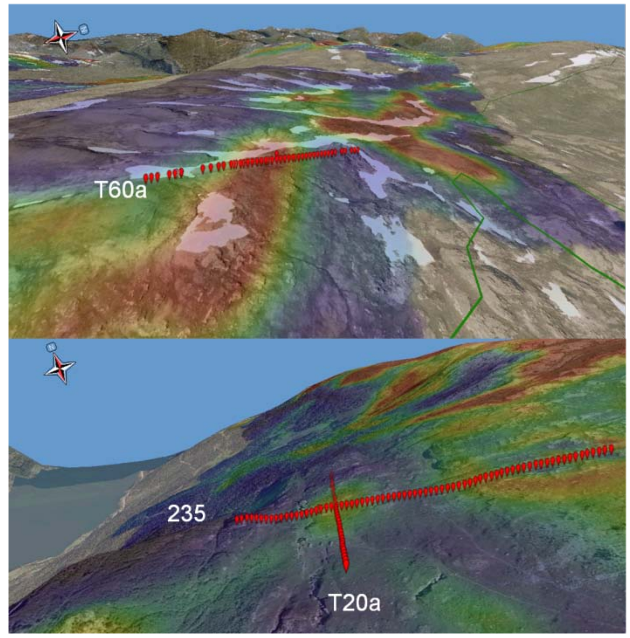

***Fig. 5 -** The three ERT profiles acquired in 2010. The colored background is the resistivity model acquired by the AEM survey in 2009. Upper panel shows line T60a in area A close to Viddalsdammen, lower panel shows intersecting profiles T20a and 235 in area B close to Joasete. Line T60a is 500m long striking NNE, line 235 700m ESE, and T20a 400 m NNE. Resistivity color scale according to Figure 2.*

This section summarizes results from a 3-day resistivity survey. Three profiles were acquired in 2 different areas (Figure 5). One line (T60a) was laid out close to Viddalsdammen with the aim to match the AEM anomaly in area A with the known outcropping phyllite/gneiss interface. The ERT profile is approximately align to tie-line 60 of the AEM survey (hence T60a). Two crossing lines were set up adjacent to Joasete (area B) crossing one of the major tension cracks in the area (Figure 6) as well as one of the creeks, potentially responsible for the movements in the area. The ERT lines also cross a minor anomaly in the AEM data. The profiles are aligned with AEM line 235 and approximately with tie-line 20.

Data quality was generally good, contact resistance better than expected for such an environment (less than 50 kΩ). Profile T60a proofed to be most challenging as it crosses several patches of up to 1m thick snow overlaying frozen ground.

Resistivity and IP data were processed and inverted with standard 2D smooth inversion (Loke & Barker, 1996).

Fig. 6 - *ERT cable crossing a large tension crack in the Joasete area*

ERT vs. AEM

All dominant features in the AEM data are evident in the ERT results. Detailed joint interpretation and inversion of the AEM and ERT data is pending, however. The results presented here are only initial snapshots. For T60a the similarity between ERT and AEM is striking, even in a quantitative sense (cross-sections in the Figures below have the same color scale for ERT and AEM!). For line 235, however, the features seen in the ERT are not so clearly comparable to the AEM sections. The main conductor close to the crossing point with T20a seems to correspond to the faint, dipping anomaly in the centre of the AEM profile. The strong conductors in the AEM are, however not evident in the ERT. This might be due to the limited penetration depth of the ground profiles.

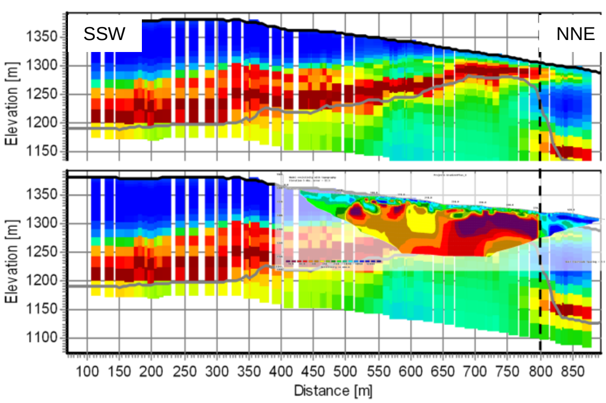

Fig. 7 - *Upper: AEM profileT60 acquired in area A west of Viddalsdammen. Bottom: corresponding profile overlain by ERT section. Co-location and scaling is approximate.* Resistivity color scale according to Figure 2. Vertical, stippled line indicates mapped phyllite / gneiss interface location.

Interpretation

Profile T20a provides an accurate image of the gneiss / phyllite interface (Figure 7). The AEM inversion results lack the lateral resolution to image a vertical structure as this fault with a ~100 m throw separating phyllite and gneiss in this area. The vertical interface between conductor and resistor in the ERT sections aligns exactly with the transition from phyllite (in the south) to gneiss found during field work.

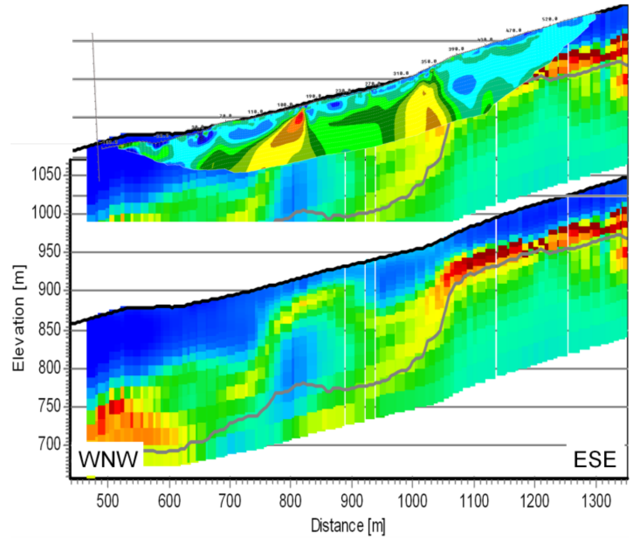

Fig. 8 - *Bottom: AEM section along line 235 from rock slide area B north of Joasete. Upper: AEM results overlain by ERT section. Co-location and scaling is approximate.* Resistivity color scale according to Figure 2

The ERT cross lines at Joasete indicate a conductive zone dipping towards NNW with some 40 – 50° dip (Figure 9). This potential sliding plane crops out exactly where the profiles cross the creek north of Joasete. This conductor might be an active sliding plane, pushing towards the big open tension crack visible in Figure 6. The Joasete creek seems connected to that sliding plane or possibly fault. Detailed analysis with instrumented drill-holes and hydrological monitoring is pending.

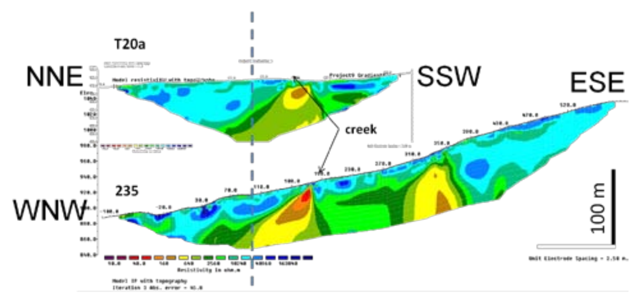

Fig. 9 - *ERT lines T20a and 235 intersecting at the blue dashed line. Resistivity color scale according to Figure 2*

Chargeability results

The IP data quality is not at its best as the survey was within the testing phase of the fairly new *Terrameter LS* system. The LS is a very advanced time-domain IP system that needs a fair amount of parameter fine tuning for perfect results. Some of the chosen parameters were not ideal at the time of this survey.

Aim of the IP measurements was to assess the presence of graphite as a potential reason for the very high conductivities. Numerous isolated anomalies can be found in both profiles (e.g. shown for line 235 in Figure 10) and they are likely related to heterogeneities in the resistivity structure of the subsurface. Chargeability is correlated to resistivity and IP artifacts at sharp resistivity interfaces are commonly observed.

Most importantly none of the isolated IP anomalies coincides with the conductive structure observed in the ERT sections. We thus conclude that significant concentrations of graphite are unlikely to be found in this area. The magnitude of the observed chargeability compares well to our experience with Norwegian clays and bedrock.

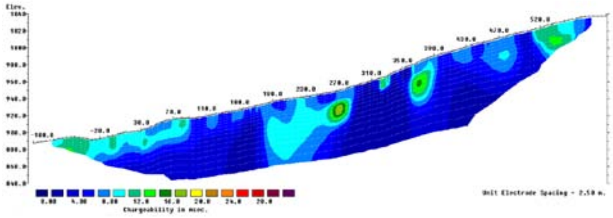

***Fig. 10** – Chargeability results of line 235 (color scale spans 0 to 30 ms with green at ~15ms).*

Discussion

Aim of the Airborne Electromagnetic (AEM) and ERT surveys was to find conductive clay within resistive phyllite. The concept of this geophysical / geohazards investigation is that on weakness zones phyllite tends to get crushed up and re-worked to its "parent"-mineral clay.

Clay and shale have low resistivity overlapping in range with graphite (Figure 4). Unweathered igneous or metamorphic rocks, however, are characterised by very high resistivity of several thousand Ωm. ERT is consequently an ideal tool to distinguish between soft, water saturated sediments and massive rock. This can be used both for overburden thickness mapping or to map lateral anomalies due to faults, fracture zones or similar weakness zones.

Conclusion

The evidences from ERT, AEM and structural analysis combine to a perfect alignment of a low resistivity zone (clay) outcropping on the bed of a creek meandering towards the creeping rock slide area. Other causes for the conductive anomaly than weak rock where out ruled by virtue of reference measurements at a known geological contact and by testing for anomalous mineralization with IP measurements.

Guided by one isolated AEM anomaly, further detailed ERT follow up provided a structural model of a dipping weakness zone (potentially sliding plane). Only drilling information, however, can provide a final answer.

This success illuminates only one of the many unstable areas around Joasete – Stampa, however, and the remaining areas need similar detailed follow up. This is especially true for the areas with maximum known rock movement. Sophisticated geophysical surveys can guide towards ideal drilling positions and will fill-in the gaps between the spot information drillings provide, finally reducing the costs of the overall project (no need for numerous drillings).

Acknowledgements

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