Airborne EM mapping of rockslides and tunneling hazards

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We have investigated potential rockslides in Western Norway using a time- and cost-efficient airborne electromagnetic (AEM) survey approach. 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 AEM survey. Based on indications that precipitation drives the reported rockslide movements, the local municipality and regional hydroelectricity company are evaluating the option of draining the unstable area to a nearby hydropower reservoir using a drainage tunnel of more than 10 km. We conducted the AEM mapping survey to locate the sliding planes and to investigate the tunnel corridor for areas with potential tunneling hazards. Spatially constrained inversion of the data set (250 km) reveals extended conductive zones interpreted as sliding planes and/or gneiss/phyllite interface. Detailed follow-up of these initial results is planned with targeted percussion drilling and ground resistivity surveys.

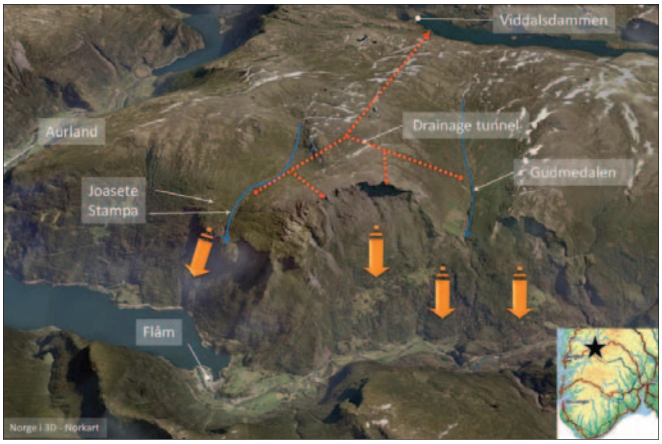

Figure 1. *Study area (aerial photography draped over topographic model courtesy of* www.norgei3d.no*) indicating areas with known previous rockslides and creeping movements (orange arrows) of both massive rock (fjord) and loose debris (valley) partly driven by pore water delivered by the Stampa and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

Introduction

The inner Aurland Fjord with the adjacent Flåm Valley (in western Norway) are among Norway's most famous tourist destinations with up to 450,000 visitors and more than 100 cruise ships a year visiting the area. The main road between Oslo and Bergen (E16) passes through Flåm, bypasses the fjord, and enters the 24.5-km Lærdalstunnelen in Aurlandsvangen. Evidence of large rockslides in the geological past has been documented in the area with ground movements evident to the present day. The area is subject to potential rockslides composed of creeping rock and debris masses (Figure 1). The intent of our study was to provide geophysical input to the ongoing natural hazard assessment program in Aurland municipality.

Based on repeat GPS measurements and anecdotal observations in the area, rock and debris movements are influenced by precipitation and snow melt. Based on this empirical evidence, the local municipality and regional hydroelectric company E-CO Vannkraft are evaluating the potential of draining the unstable area to a nearby hydropower reservoir (Viddalsmagasinet) with the aid of a 10-km tunnel. Initial interpretations of an airborne electromagnetic (AEM) mapping survey conducted in June 2009 reveal indications of the sliding planes and assess the tunnel corridor for potential tunneling hazard areas.

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

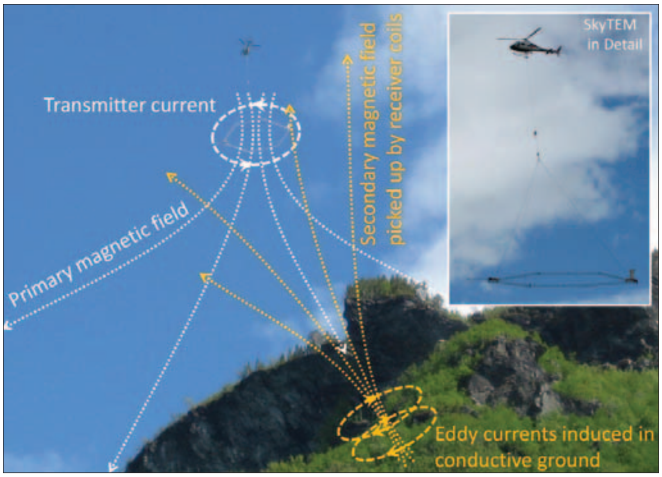

Figure 2. *Fundamentals of AEM. A helicopter-towed wire loop induces electrical eddy currents in conductive ground, inducing a secondary magnetic field picked up by receiver coils. Background photo shows the escarpment in area C sliding downhill at 1–3 cm per year.*

AEM survey

Unstable rock in the study area, approximately 1000 m above sea level, has been mapped as massive phyllite broken by numerous tension cracks with openings up to several meters. Field observations also document significant amounts of surface water in streams on the mountain plateau around

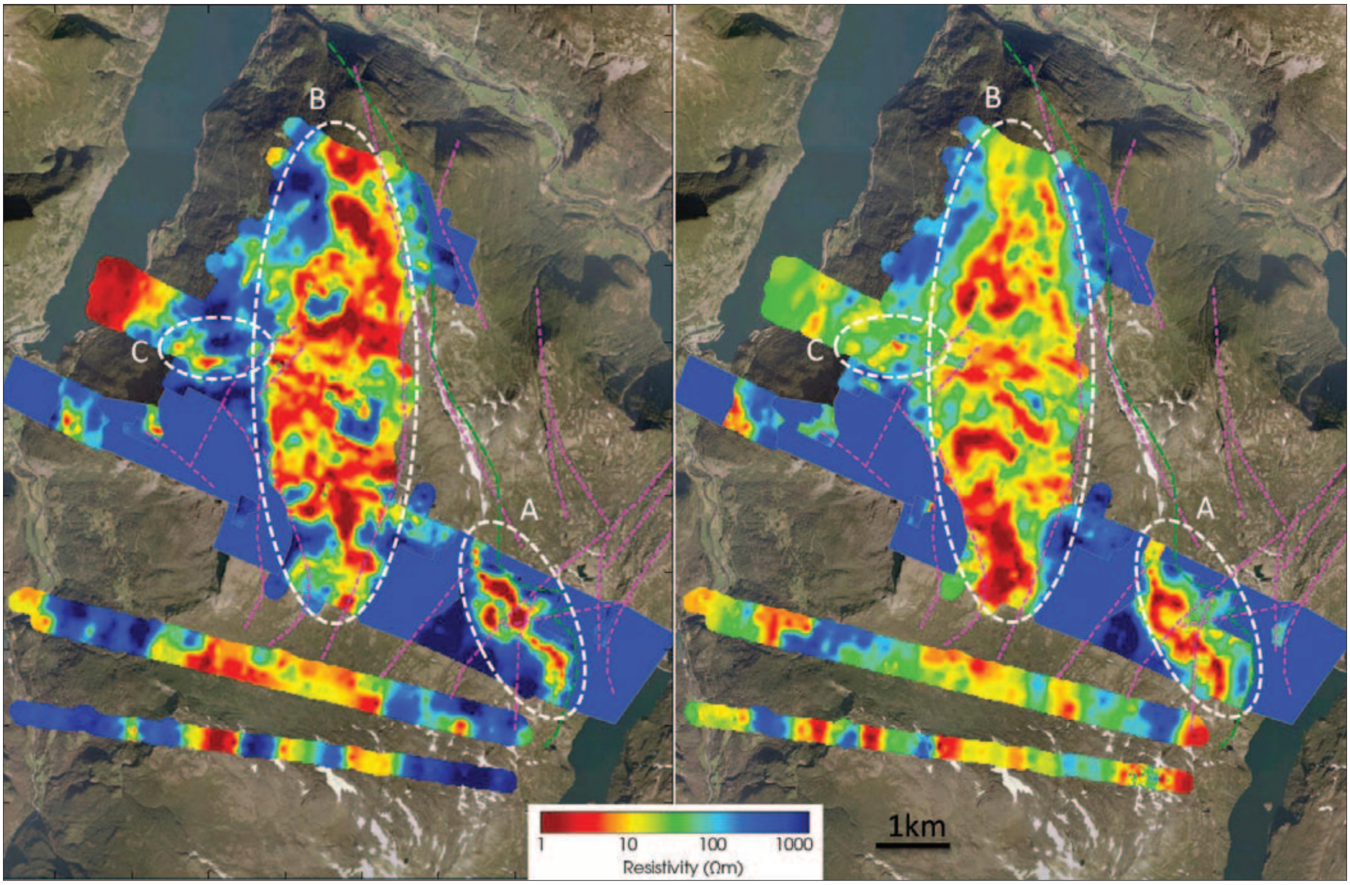

Figure 3. *Spatially constrained inversion (SCI) result. Interval resistivity averaged 40–50 m (left panel) and 100–110 m (right panel) below ground (depth slice) mapped over survey area. Purple and green lines roughly outline mapped weakness zones and phyllite/gneiss interface, respectively. Bright blue areas are areas where minimal AEM signal was recorded due to highly resistive ground.*

Joasete (Figure 1) that disappears into some of these cracks and reappears on the surface several hundred meters down the slope. Potentially sliding planes provide pathways for the water with changes in water pressure potentially causing instability. Because the phyllite can be crushed to fine-grained clay under certain conditions, the water-saturated sliding planes should be an ideal target for AEM because they are conductive (1–10 Ω•m), compared to the more resistive, undisturbed phyllite or nearby gneiss (> 1000 Ω•m). Earlier ground resistivity measurements in the area strengthen this hypothesis. Note that these geological conditions are in strong contrast to other Norwegian rockslides, like Åknes, which is within a gneiss where resistivities of several thousands (up to 10,000) Ω•m are possible even in the water-saturated zones (Heincke et al., 2010).

The AEM survey was carried out with SkyTEM, a helicopter-borne, time-domain EM system (Figure 2; Sørensen and Auken, 2004). In total, 250 km were flown at 125-m line spacing with some infill lines in the central part of the survey area. To improve lateral resolution in this area of large topographic relief, flight speed was a nominal 7 m/s at 30 m above ground (sensor height). The system was operating with two relatively low transmitter moments tuned specifically for high-resolution near-surface mapping: 63 kA m^2 and 2.5 kA m^2 at 100 Hz and 200 Hz base frequencies, respectively, with a 60% duty cycle. This setup led to off-time windows from 8.4 μs to 2.5 ms. Standard processing and spatially constrained inversion, SCI (Viezzoli et al., 2008), generated resistivity maps and profiles. Only the vertical magnetic field component (H_z) was considered for inversion. Because SkyTEM also acquires the horizontal field component (H_x), future analysis and interpretations could include 3D data components.

Results

Our preliminary AEM data interpretation found widespread areas with high conductivity, most likely caused by either water-saturated, fine-grained sliding planes or fault zones at the phyllite/gneiss interface (Figure 3). Based on our initial survey concept, we expected limited signals from phyllite that had been reworked to clay but no significant response from the undisturbed phyllite and gneiss environments. Much to our surprise, we found strong and consistent signals covering nearly the entire survey area (Figure 3). In the following, we highlight some examples; however, we are only beginning to understand the subtleties of the processed data:

- Some flight lines were extended over the fjord to test the bathymetry-sounding capability of the SkyTEM system. Because the fjord is filled with old debris, the water col-

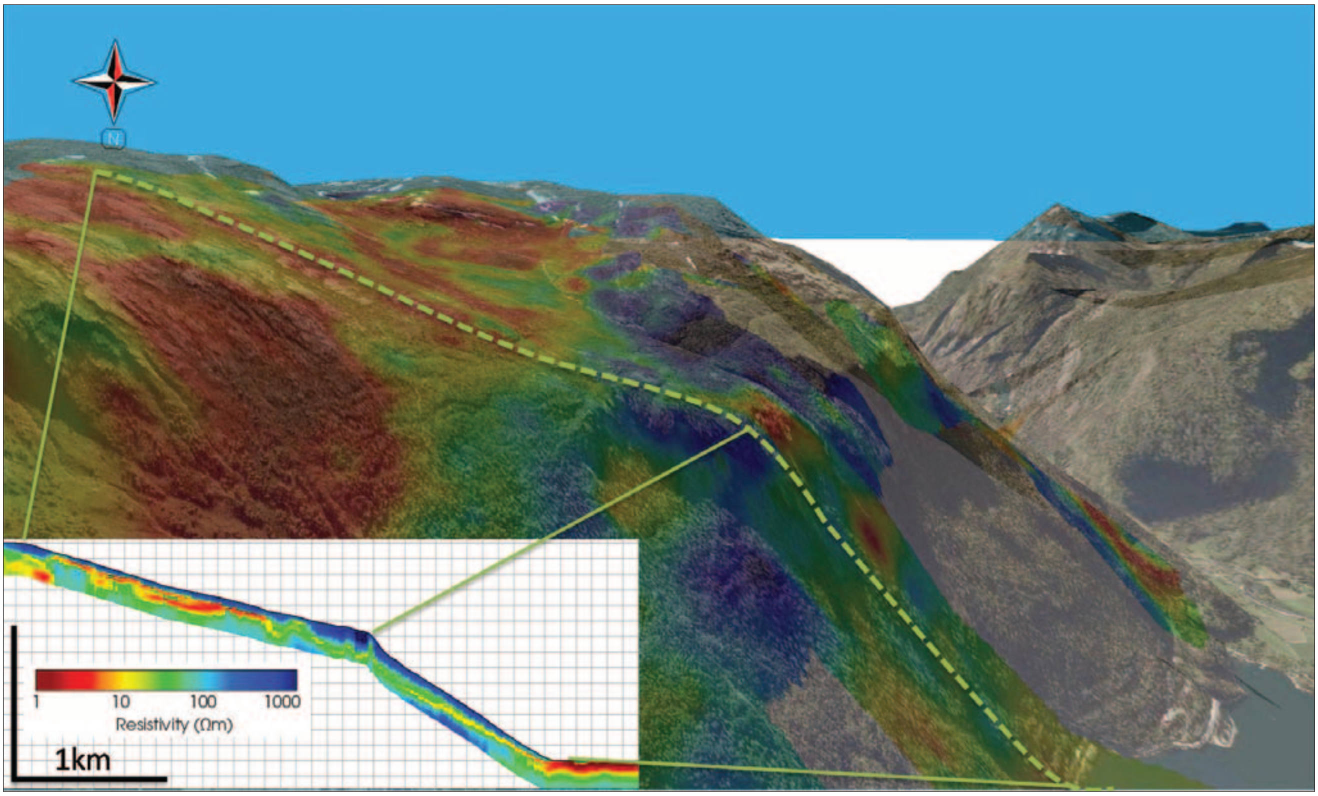

Figure 4. *3D visualization of area C around Joasete (Figure 3) looking south. A slightly transparent aerial photo is draped over topography with no vertical exaggeration. The 70–80 m resistivity depth slice draped 75 m below the topography shines through the aerial photo. A conductivity depth section derived from SCI results represents a cross section at the profile indicated with a green, stippled line.*

umn was expected to be shallow enough (< 50 m) for complete signal penetration. The high conductivity of the sea water is evident in the shallow (40–50 m) resistivity map (Figure 3, left), while the deep (100–110 m) depth slice probes the seafloor (Figure 4, right). The conductivity depth section from multilayer, smooth inversion (Figure 4) shows the limited thickness of the conductor (sea water). Further, four-layer inversion (not shown) indicates water depths between 40 and 60 m, which is in remarkably good agreement with bathymetric charts indicating depth ranges from 43 to 59 m in the area.

- A meandering distinct conductor close to Viddalsdammen roughly coincides with the phyllite/gneiss boundary known from surface mapping (Area A, Figure 3). Following the feature through different depth slices indicates a fairly flat dip to the southwest (Figure 5).
- Consistent from line-to-line, and covering a large area (some 10 × 2 km) 10–80 m below the surface, is a massive conductor that expands to a thickness of up to 100 m (Area B, Figure 3 and Figure 4). Given the inductive nature of the AEM measurements, the depth to the base of the conductor can be only roughly estimated. The data indicate clearly, however, that a resistor underlies that structure. Generally the conductor dips conform to the topography. The lateral extent of this feature frequently co-aligns with topographic or geological features (Figure 3).
- The subsurface around Joasete and also along the slopes down to Aurlandsfjorden and Flåmsdalen features widespread conductive anomalies (Figure 4). The debris-covered slopes usually feature consistent, thin conductors while the anomalies at Joaste and Stampa (Area C, Figure 3) are more complex, most likely caused by subvertical 3D structures.

Discussion

Even though we have gained significantly more information about the area's geology from the AEM survey, care must be taken when interpreting the measurements. Even though SkyTEM is a versatile system for rough topography (slow flight speed, acquisition of system altitude and attitude with lasers and inclinometers), the SCI algorithm has been designed for efficient mapping of layered structures with limited topography both on the surface and the geology. Here we are faced with a high relief (up to 80%) and evidence of strong 2D and 3D contrasts that exceed the assumptions and approximations which apply to SCI processing. Hence, detailed follow-up of 3D artifacts in the results involving the acquired H_x component is crucial before final decisions are made.

Conclusions

Based on the geophysical data and knowledge from geological pre-investigations, we can draw the following preliminary conclusions:

- The known, outcropping phyllite/gneiss interface close to

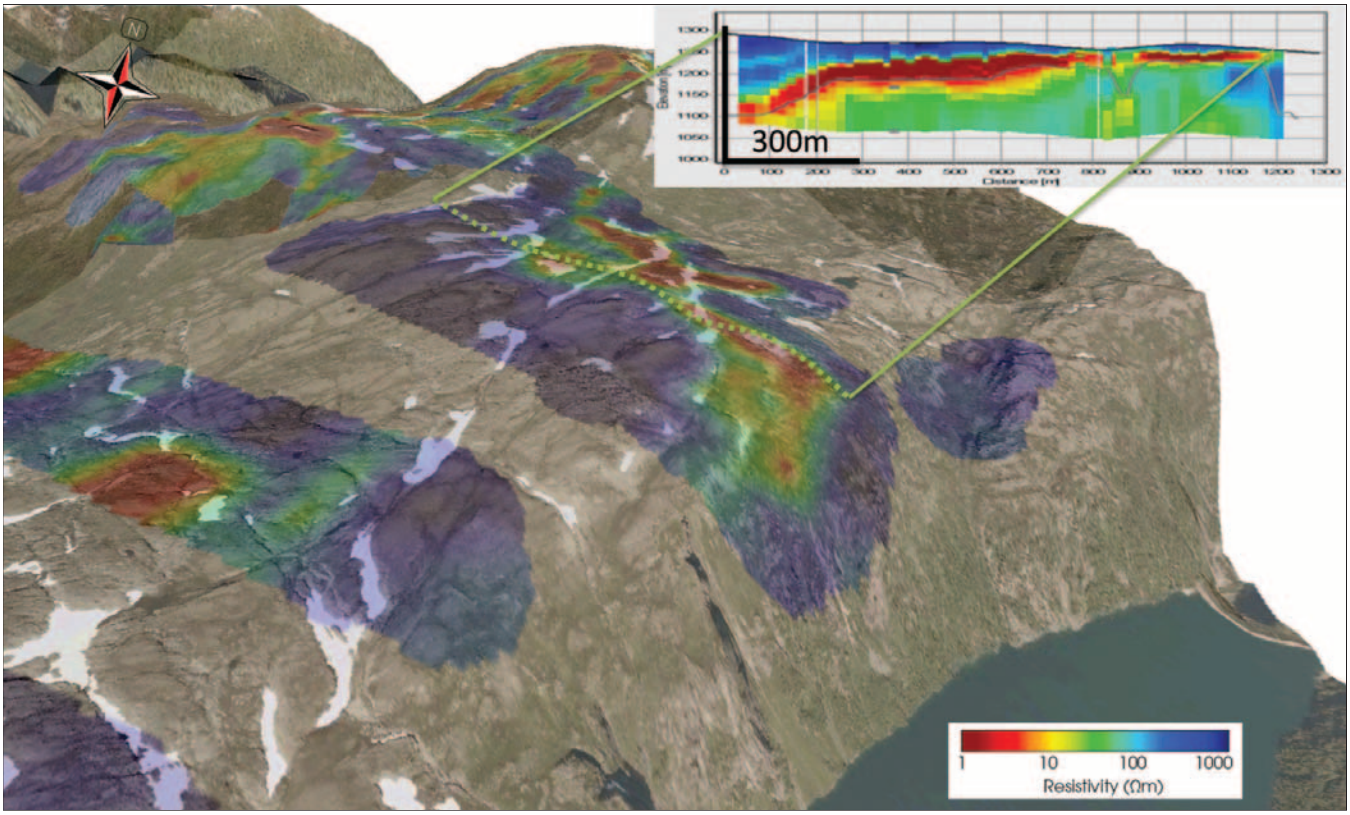

Figure 5. *Area A adjacent to Viddalsdammen (Figure 3) looking NNW. The 30–40 m resistivity depth slice is draped 35 m below the topography. For a more detailed description refer to Figure 4.*

Viddalsdammen (Area A, Figure 3 and Figure 5) appears as a strong conductor dipping southwest, consistent with outcrop data. This indicates the presence of crushed phyllite (potentially with graphite infill), thereby representing a formerly unknown potential tunneling hazard.

- A similar feature appears over large areas on the west flank of the mountain plateau (Area B, Figure 3 and Figure 4), which may indicate a thin, 50–150 m layer of phyllite overlaying gneiss.
- More complicated anomalies appear around Joasete (Area C, Figure 3), potentially indicative of the anticipated sliding plane response. Further down the slope a consistent, conductive layer most likely indicative of the base of a debris field filled with fines and thus the sliding plane for the creeping debris along the fjord and valley.

No final conclusions can be drawn from geophysical data alone, however. At this point, only limited drilling is necessary to transform the geophysical maps to a firm geological model. We are planning a ground follow-up survey with electrical resistivity tomography to gain 2D or 3D information on the structures. The intent is to further distinguish clay from phyllite containing graphite by virtue of the induced polarization response. TLE

References

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