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Quantitative Depth to Bedrock Extraction from AEM Data

H. Anschütz (NGI), C. Christensen (Queen's University) & A.A. Pfaffhuber* (NGI)

SUMMARY

A new road segment is being planned northeast of Norway's capital city, Oslo. In this context, knowledge of sediment thickness is vital, as is information about occurrence and extent of highly sensitive marine clay (so-called quick clay).

Airborne EM measurements were conducted to provide information of depth to bedrock/sediment thickness between drilling sites and guide the further drilling program. AEM data indicate a variable bedrock depth with a general trend towards shallower bedrock in the northeastern part of the investigation area. Quick clay is not easily identified in the AEM data, but some possible occurrences agree well with the results from drillings.

Various methods for estimating depth to bedrock were compared: (1) Using a constant resistivity threshold either survey-wide or for each profile line; or (2) by using an appropriate resistivity value as a function of position. A contouring algorithm was developed to for the second method to incorporate both borehole and AEM data and hence account for apparent variations in resistivity at the sediment-bedrock boundary. Though both exhibit the same general trends, predictions for some locations differed significantly. Based on the AEM results recommendations for further drillings were given, thus reducing the overall costs of the project

Introduction

To complete a new, major highway linking East Norway with Sweden, the E16 from Kløfta to Kongsvinger some 50 km NE of Oslo, 32 km new motorway are planned from Nybakk to Slomarka (Figure 1). As part of the geotechnical design, we supplemented the geotechnical ground investigation - drilling programme with geophysical measurements. As the area is comparably large for ground-based measurements, we carried out an airborne electromagnetic (AEM) survey. The aim of the AEM survey was to obtain depth to bedrock and get further information about the extent of sensitive clay. Besides of areas with strong interference with cultural noise and very shallow bedrock, a clear resistivity increase with depth is observed in inversion models after pseudo-3D Spatially Constrained Inversion (SCI). Due to the complex geology and bedrock depth varying from meters to tens of meters attempts using a general resistivity threshold to mark bedrock did not delivery satisfying results. A geospatial cross correlation between drilled bedrock depth and threshold resistivity was developed and consequently applied on the full dataset, delivering a highly accurate and detailed bedrock model.

Method

The survey was conducted with the SkyTEM 302 system using a 314 m^2 frame with two turns in the high moment and one turn in the low moment to obtain high near surface resolution. A general description of the system can be found in Sørensen and Auken (2004). Here, the full sounding curve comprising all available time gates covers the time interval from 4.43 μs to 4.636 ms. A total of 34 gates were recorded. Raw data were processed using the *Århus workbench* (www.aarhusgeo.com) and inverted to a 3D model based on 1D forward calculations (SCI, Viezzoli et al., 2008).

Survey location and extent

The survey area centers along the road corridor and extends over two known quick clay hazard zones (Figure 1). A total of 178 line-km was flown in three consecutive days in January 2013. Three parallel lines with a spacing of 25 m were flown along the planned road corridor. In addition, 15 lines were flown near Vorma/Vormsund and 9 lines near Uåa, to cover areas of potential sensitive clay. These additional lines had a nominal spacing of 125 m.
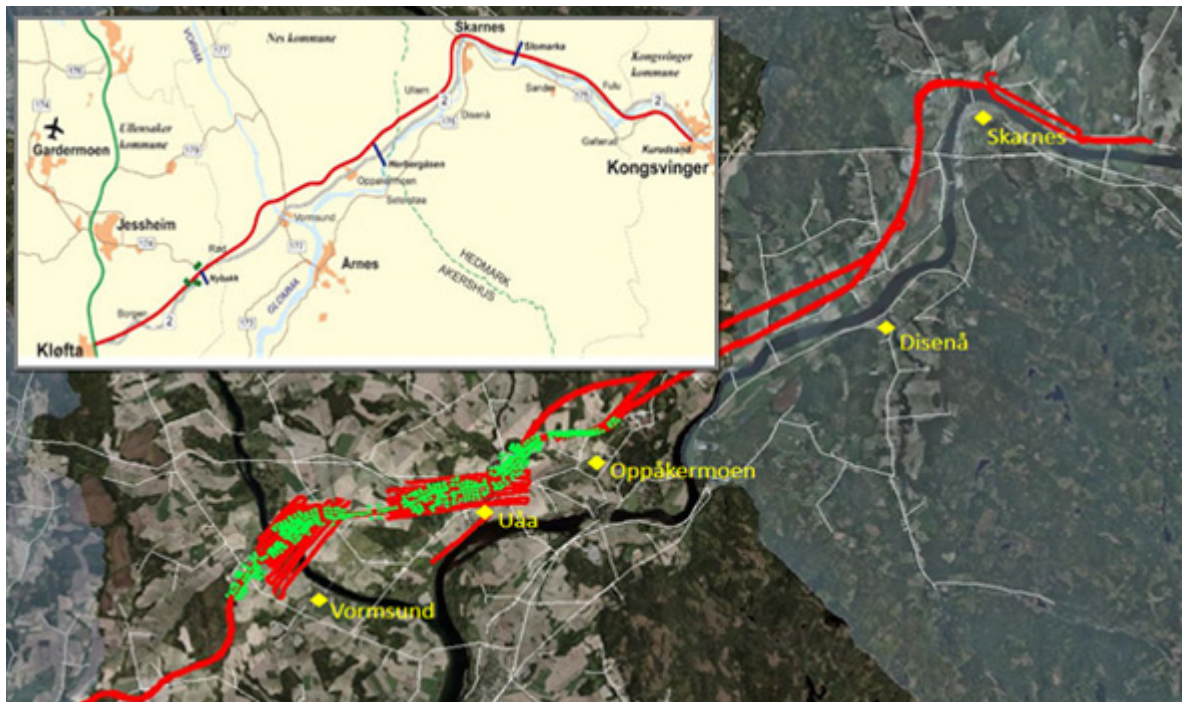

Figure 1 *Location of the road stretch under investigation (inlay) and flight lines (red) and boreholes (green) on main map. Thin white lines depict power lines.*

Results

Survey results capture the expected geological complexities in the area. There is a trend towards shallower bedrock to the northeast whereas the areas around the rivers Vorma and Uåa are characterized by deeper bedrock. In latter case, possible sensitive clay occurrences are also observed. In general, geotechnical drillings and AEM data show agreement once the limitations of both methods are accounted for. The data are in places heavily influenced by infrastructure present (such as houses, roads, power lines) that could not be avoided as the survey plan was governed by the planned road alignment. These data had to be omitted from the inversion and interpretation. Further areas had to be excluded from inversion as outcropping, highly resistive bedrock did not provide a sensible TEM response (Figure 2).

AEM resistivity sections along the flight lines clearly track the bedrock topography and in some areas indicate potential sensitive clay occurrence (Figure 3). Marine clays are characterized by resistivities between 1-10 Ωm, depicted by blue colors. The resistivity for sensitive clay is strongly site-dependent and can range from 10-100 Ωm (Rømoen et al., 2010), depicted by the green colors in the profiles. Other geological materials can have the same resistivity as sensitive clay. Thus, it is not possible to detect sensitive clay based on resistivity alone. It is likely that not all the green-colored areas in the profiles shown are sensitive clay. However, along the AEM profile between Vorma and Uåa (Figure 3), the sediment layer is thick enough that the structure within this layer can be resolved. Bedrock is both indicated by a 100 Ωm threshold and a manually picked layer, guided by the boreholes.
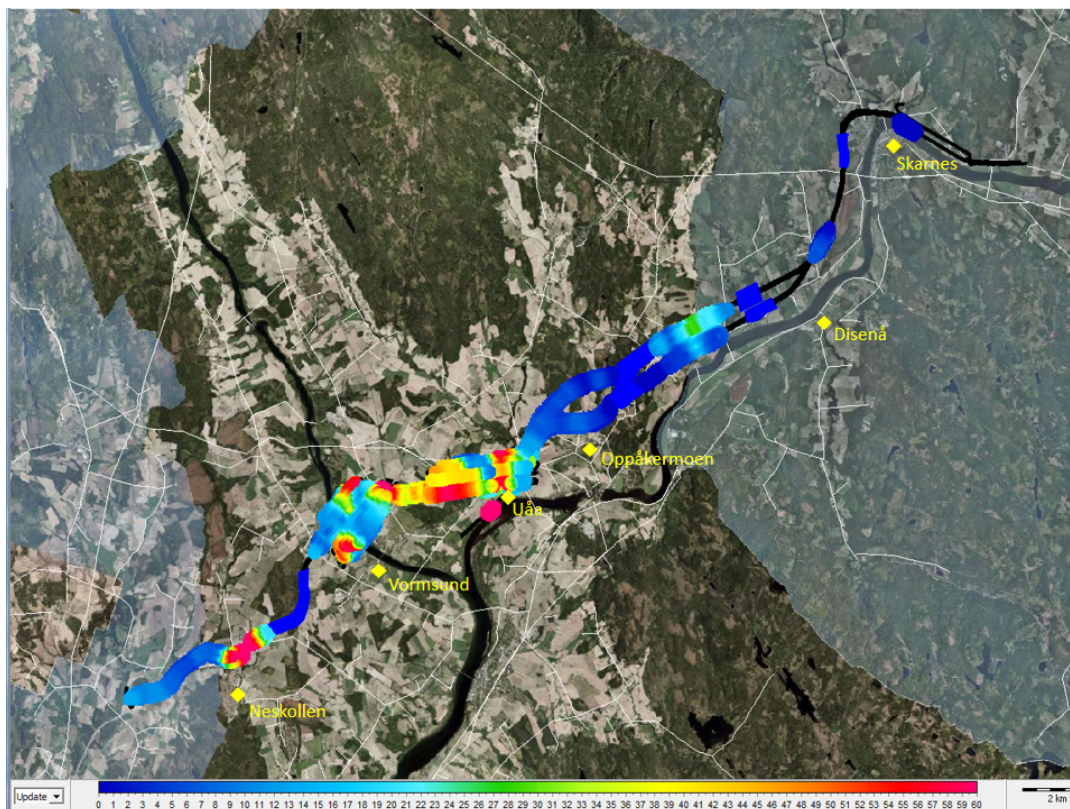

Figure 2 *Depth to bedrock semi-manually picked from AEM resistivity models. Areas where data have to be omitted but where bedrock can be assumed to be close to the surface are marked in dark blue.*

To extract a 3D bedrock model from the AEM results three different approaches were chosen: Firstly, a predefined threshold resistivity, in this case 100 Ωm based on the borehole data, was tracked throughout the resistivity cube. The resulting bedrock depth was consistent with drillings on a regional perspective (not shown). Such an approach is usually successful for data within an area of

homogeneous bedrock and quaternary geology over several hundred meters but the algorithm has only limited success for the extent of the entire survey. Given that the analysis is based on a smooth inversion model blending bedrock and sediment resistivities together at the bedrock surface determined by the actual resistivities and sediment thickness, large variations in apparent threshold resistivity must be expected.

Secondly, profiles were manually inspected and bedrock was picked based on integrated boreholes and the resistivity model (Figure 3). These manually picked bedrock interfaces, visualized over the whole survey area were not fully satisfying either, as the profile – individual interfaces cause unrealistic steps from line to line (Figure 2).
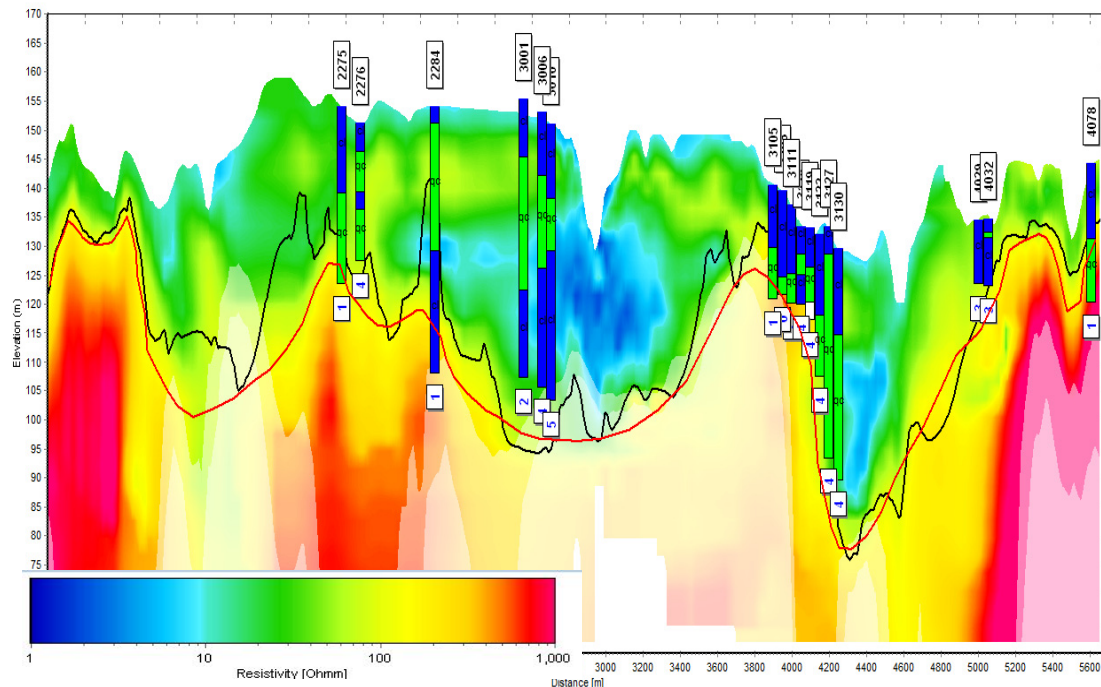

Figure 3 *AEM profile and boreholes along a profile between Vorma and Uåa. Blue borehole colours indicate sedimentary material that is not sensitive clay, green colours indicate sensitive clay. Boreholes are marked by their numbers (4 digits) and their lateral distance to the AEM profile in [m] (1 digit). The red line depicts a manually picked bedrock layer, the black line an automatically picked 100 Ωm threshold.*

Thirdly, we developed a fully automatic bedrock tracking algorithm with spatially determined threshold resistivity. The algorithm follows a three step approach, based on the SCI 3D resistivity cube and bedrock depth at the existing boreholes: First, for each borehole location the resistivity at drilled bedrock depth is extracted from the resistivity cube. Then, these threshold resistivity values are interpolated to areas where borehole and AEM data sufficiently overlap. Finally, depth to bedrock is extracted from the resistivity cube, based on the extrapolated threshold model. In our case this threshold resistivity at borehole sites varies from 100 to 800 Ωm with median at 500 Ωm.

This algorithm succeeds in tracking a discrete boundary from a heterogeneous, smooth-model (Figure 4). Similar results may be achievable with layered inversion, constrained by depths at borehole locations. We have tested such approaches but feel more confident with the smooth model algorithm. The disadvantage of constrained, layered inversion is that the constraints can locally create large inversion misfits that can be difficult to judge. Smooth inversion is more robust and can be "sharpened" through proper borehole integration as discussed.
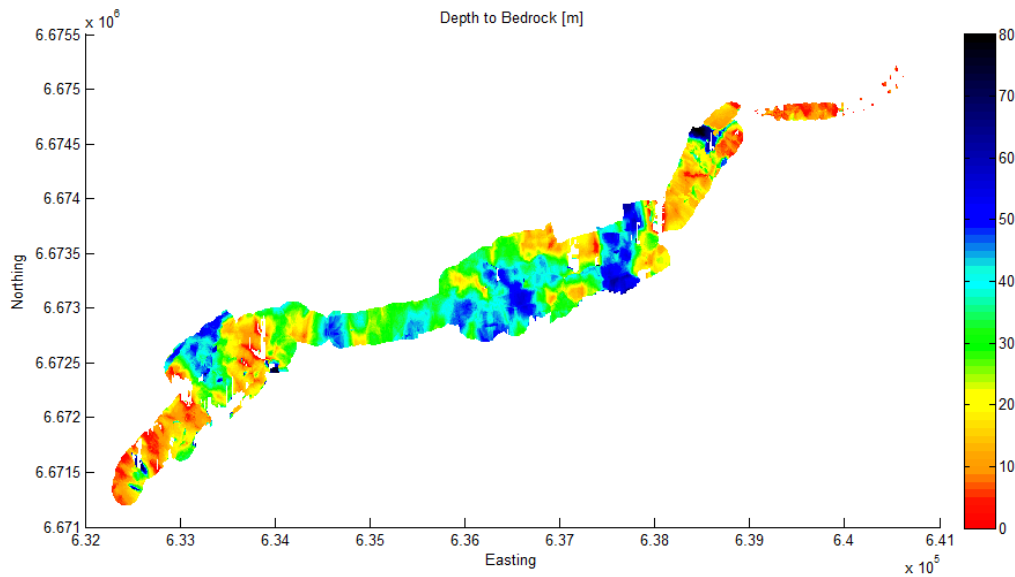
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Figure 4 *Depth to bedrock obtained from the interpolation algorithm using AEM and borehole data. The grid resolution is 10 m.*

Conclusions

For a survey of this extent over varying geology the simple approximation of one threshold bedrock resistivity is not sufficient. We thus developed an algorithm that first determines a spatial threshold resistivity model based on available borehole data and then applies this resistivity model to track bedrock between borehole locations. The result is a bedrock model that agrees with boreholes and "fills in the gaps" where no borehole data is available.

Even though the AEM survey was carried out rather late in the project, (several hundred geotechnical soundings had been drilled already) the AEM results provided a valuable database for further soil investigations and the survey costs could be amortized via savings in the drilling program. We see a huge potential for geotechnical AEM, especially where it precedes soil investigations used as a planning tool for the geotechnical work and where appropriate parameters for a constrained, layered inversion are not yet known. Properly integrated AEM combined with limited intrusive testing can provide a geo-model with higher detail and lower cost compared to purely, traditional soil investigations.

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