Combining airborne electromagnetics with geotechnical data for automated depth to bedrock tracking

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Summary

Airborne electromagnetic (AEM) was used to supplement a geotechnical investigation for a highway construction project in Norway. Heterogeneous geology throughout the survey and consequent variable bedrock threshold resistivity hindered efforts to track depth to bedrock, motivating us to develop an automated algorithm to extract depth to bedrock by combining both boreholes and AEM data. Evaluation shows that for preliminary surveys, significant savings in the number of boreholes required can be made without sacrificing bedrock model accuracy. However, AEM cannot supersede direct sampling where the model accuracy required exceed the resolution possible with the geophysical measurements. Nevertheless, with the algorithm we can identify high probability zones for shallow bedrock, identify steep or anomalous bedrock topography, and estimate the spatial variability of depth at earlier phases of investigation. Thus, we assert that our method is still useful where detailed mapping is the goal because it allows for more efficient planning of secondary phases of drilling.

Introduction

While the use of near-surface geophysics is nothing new in geotechnical engineering projects, the use of airborne methods is a fairly recent development. Airborne methods offer the potential of reducing site investigation costs by surveying large areas at a time, but they are still limited by challenges with interpretation. Manually interpreting geophysical sections with other datasets (e.g. geological cross-sections, boreholes) can lead to useful models, but this kind of appraoch (i.e. cognitive modelling) is time-consuming, subjective, and not repeatable. Quantitative methods such as constrained inversion are more repeatable and objective, but these are limited to cases with very simple geology (Foged et al. 2014).

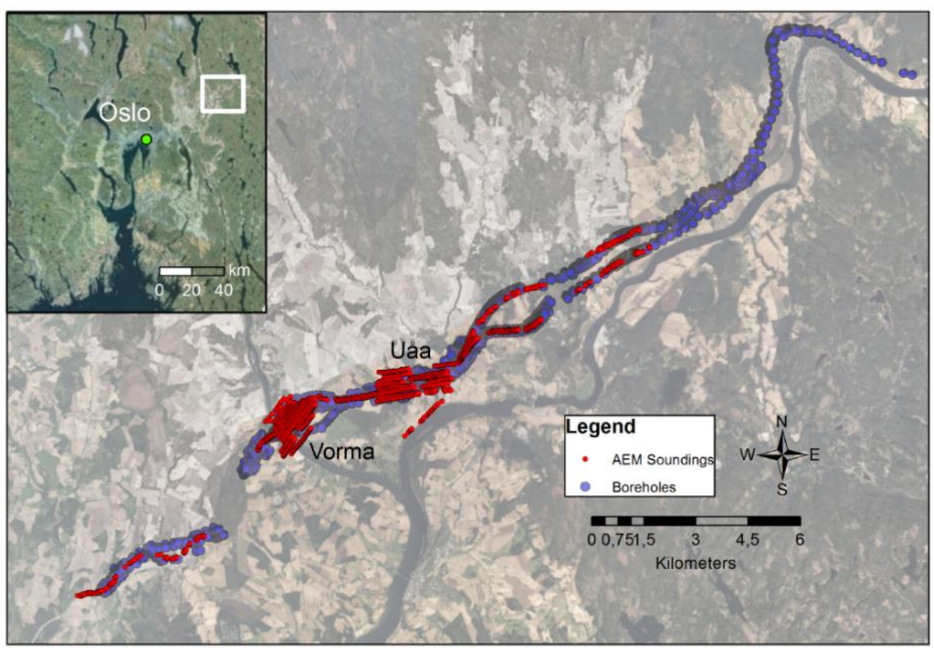

FIGURE 1. LOCATION MAP FOR DATA COLLECTED FOR THE E16 HIGHWAY UPGRADE SITE INVESTIGATION, WITH AN INSET MAP SHOWING THE SURVEY LOCATION RELATIVE TO OSLO, NORWAY. VORMA AND UÅA ARE THE NAMES OF TWO WATERCOURSES CROSSED BY THE AEM SURVEY.

This was the dilema our team faced during a site investigation for a 30 km section of the E16 highway being upgraded northeast of Oslo, Norway. An airborne electromagnetic (AEM) survey was used to, among other aims, map depth to bedrock and to fill in data gaps between the 1388 drilling locations (Figure 1). However, in this area, there are large variations in overburden composition (ranging from conductive glacial clays to more resistive post-glacial fluvial sediments) and local fluctuations in bedrock composition, ranging from biotite-rich gneisses and mica schist. Hence, while the resistivity model produced from the AEM showed similar trends to the borehole logs, the resistivity at known bedrock depths varied between 60 and 2000 Ωm. Trying to extract the depth to bedrock from the AEM model with a constant resistivity threshold yielded a bedrock surface that matched poorly with borehole logs. Similarly, we produced a bedrock topography model by manually integrating data sets, but we lacked a reliable way to quantify uncertainty. To address the issue, we sought out to create an automated algorithm which would: (1) determine depth to bedrock by combining borehole and AEM data; (2) account for variable bedrock resistivity; and (3) provide a depth uncertainty estimates.

Method

AEM data was acquired using a helicopter time-domain system, specifically the SkyTEM 302 system with a 314 m^2 frame described by Sørensen and Auken (2004). A total of 178 line-km were flown over three consecutive days in January 2013. Given the complexity of overburden sediments, a smooth, pseudo-3D spatially constrained inversion using Århus Workbench provided the best resistivity model. The inversion model has 20 layers of logarithmically increasing thicknesses, ranging from 1.5 to 12.4 m. Further details about geophysical inversion and processing can be found in Anschütz (2014),

The depth to bedrock measurements at borehole locations and the vertical resistivity profiles at AEM sounding locations are not co-located. To find an appropriate depth to bedrock using a variable resistivity, four computational steps are used:

Step 1. At borehole locations, determine bedrock threshold resistivity by interpolating AEM data.
Step 2. At AEM sounding locations, determine bedrock threshold resistivity by interpolating Step 1 results.
Step 3. At AEM sounding locations, determine depth to bedrock using Step 2 results, vertical resistivity profile, and an initial guess from borehole locations.
Step 4. Interpolate depth to bedrock on a regular grid using borehole measurements and Step 3 results.

Two variations on the algorithm were developed using different interpolation and depth selection functions. Variation 1 uses simple inverse distance weighting interpolators and selects depth to bedrock using the intersect of the bedrock threshold resistivity and the vertical resistivity profile (Figure 2A). Variation 2 instead uses ordinary kriging for interpolation. (In Step 1, rather than full 3D kriging, interpolation is done within AEM inversion model layers as in Pryet et al. (2011)). Additionally, Variation 2 combines multiple probability distribution functions to find depth to bedrock in Step 3 (Figure 2B). Thus, Variation 2 allows uncertainty estimates to be carried through successive interpolation calculations.

Application

The two variations were first applied to the entire data set. Figure 3 compares interpolated depth to bedrock maps created using Variation 2 either by including or excluding AEM data. While there is a visible improvement in coverage of the depth map and reduced uncertainty, the improvement is limited by issues in data quality. Approximately 35-40% of all AEM soundings did not provide a valid depth selection. This was mostly because AEM data at those sounding locations had to be discarded due to anthropogenic noise or low signal. Variation 1 was further unable to find a depth to bedrock in a further 2-3% compared to Variation 2 because an exact match in threshold resistivity could not be found.

Thereafter, cross-validation was done where random numbers and combinations of boreholes were excluded as model input and algorithm predictions at those locations were compared to measured values. The results of these trials for Variation 2 are given in Figure 4. When few boreholes are available to the algorithm, the improvement in accuracy achieved by including AEM data is significant, but the degree of improvement varies by location. In most areas, bedrock is nearly flat, so adding AEM does not add more detail in most location. Yet, in areas with rapidly changing bedrock depth (e.g. river valleys), incorporating AEM data improves depth prediction accuracy significantly. As more boreholes become available, however, the comparative advantage of including AEM data decreases, with the crossover point being near the lateral resolution limit of the AEM survey (approximately 100 m).

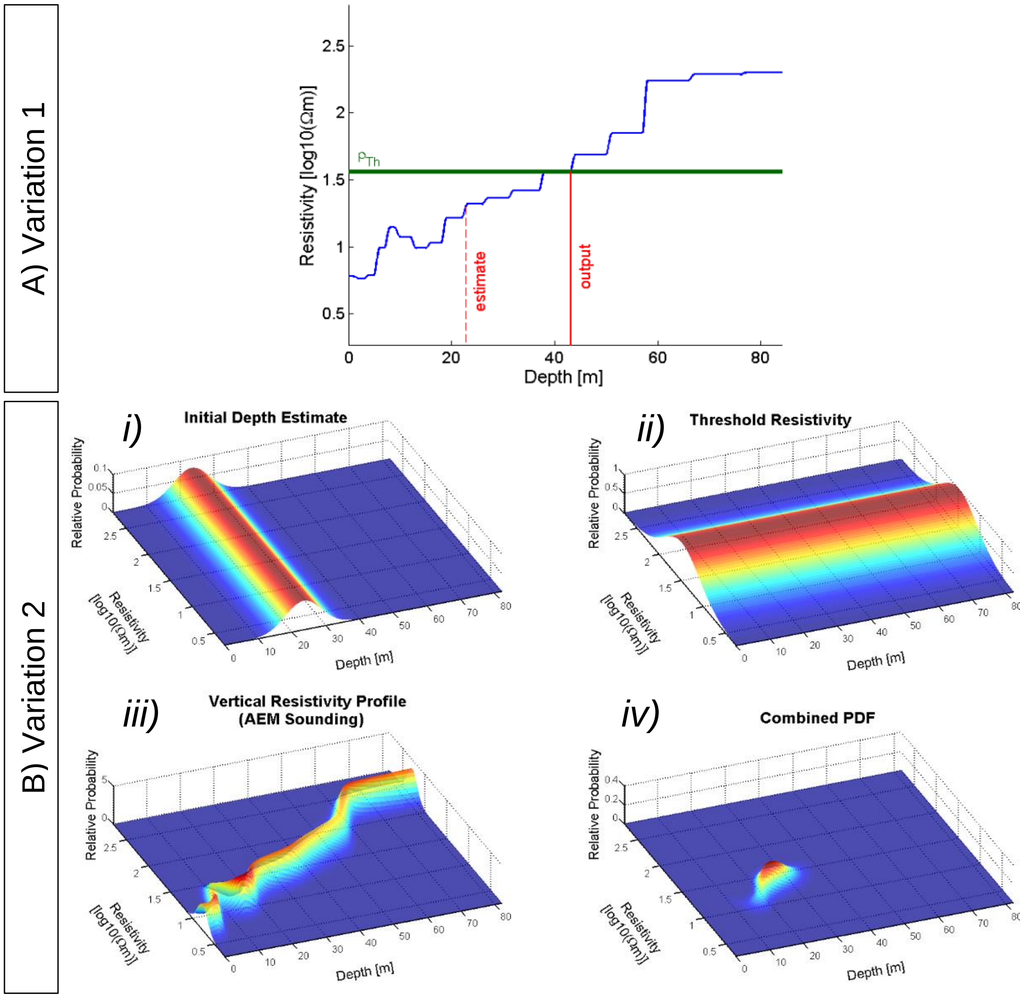

FIGURE 2: COMPARISON OF THE DEPTH TO BEDROCK SELECTION METHODS EMPLOYED IN STEP 3. A) VARIATION 1 USES SIMPLE INTERSECTION OF THE VERTICAL RESISTIVITY PROFILE AND THRESHOLD RESISTIVITY. B) VARIATION 2 EMPLOYS MULTIPLE PROBABILITY DISTRIBUTION FUNCTIONS

Conclusions

The algorithm that we have developed is a time-efficient method for combining AEM with geotechnical data to get depth to bedrock. Compared to earlier cognitive modelling approach, we were able to produce a depth to bedrock map much more quickly and able to quantify model uncertainty. In this case, while there was a clear resistivity contrast between bedrock and overburden, the improvement in bedrock model accuracy that adding AEM data provided was limited by cultural noise, low signal, and by the resolution of geophysical method itself. Nevertheless, we have shown that in early phases of drilling, our method provided substantial improvements in depth model accuracy. By using this tool in early phases of investigation to inform and refine later phases of drilling, major cost savings may be possible. This may be especially relevant where resistivity models or for a project location are already available from a third party (e.g. from a geological survey for mineral exploration) and additional survey costs do not factor in.

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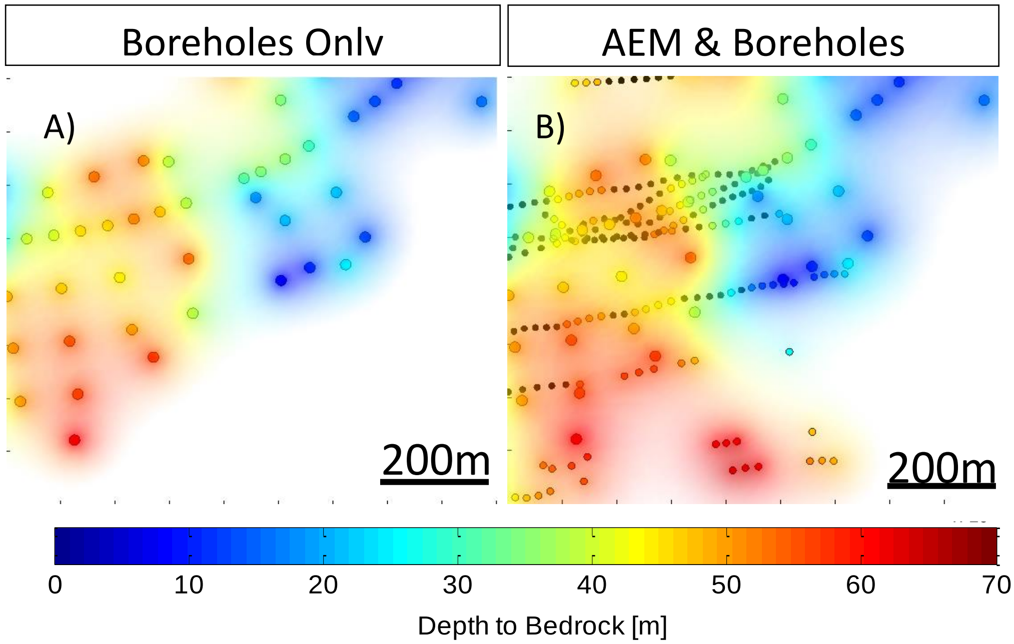

FIGURE 3 COMPARISON OF THE OUTPUT DEPTH TO BEDROCK GRIDS USING VARIATION 2 WHEN AEM DATA IS EXCLUDED. SMALL BLACK DOTS INDICATED AEM SOUNDING LOCATIONS WHERE NO VALID DEPTH TO BEDROCK VALUE WAS FOUND. WHITE TRANSPARENCY OVERLAY INDICATES UNCERTAINTY ESTIMATE AT THAT LOCATION.

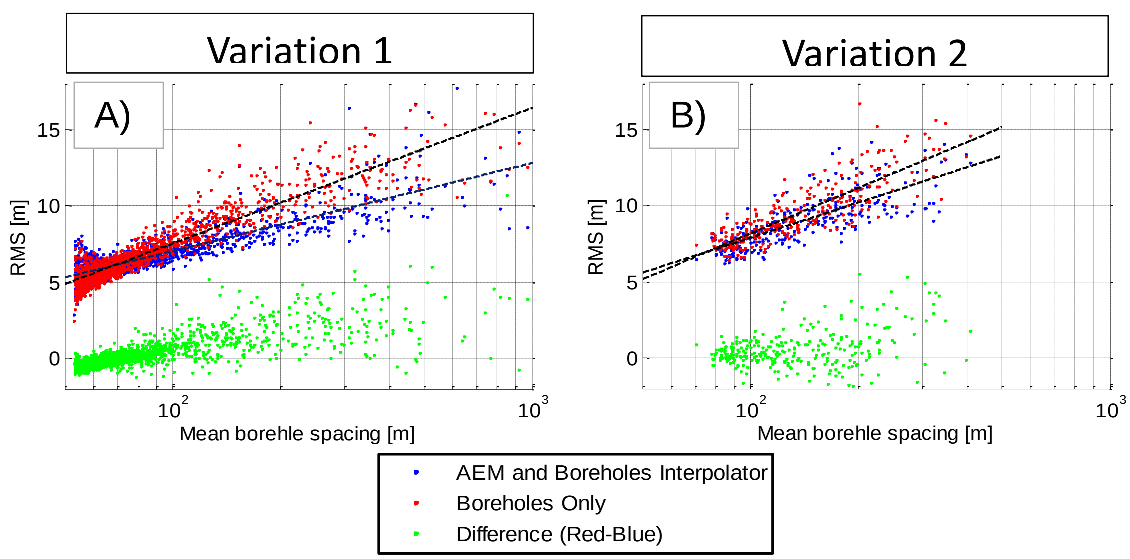

FIGURE 4: RESULTS OF THE CROSS-VALIDATION SHOWING RMS ERROR OF THE BEDROCK DEPTH PREDICTIONS VERSUS MEAN SPACING OF THE INPUT BOREHOLES.

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