Stretching AEM near-surface resolution limits related to low- and very high resistivity contrasts

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SUMMARY

Data from AEM surveys carried out in Norway, to support ground investigations for infrastructure projects, were used in this study. In large infrastructure projects, knowledge of sediment thickness is vital, along with information about sediment type as possible occurrence of highly sensitive clay. The acquisition systems, calibration and data processing are continuously improved to increase the sensitivity of the AEM systems.

In an area with conductive shales over resistive bedrock, the recently introduced *system response* method was tested. It is applied in the inversion of SkyTEM data and makes it possible to utilize the very earliest time gates, providing information about the shallower layers. The models showed to give more pronounced structures in the near-surface, reflecting true structures observed in resistivity borehole measurements. The same outcome was observed when conducting synthetic modelling.

In another setting AEM measurements were carried out along a planned road project to provide information about the extent of very conductive, possible alum shale. A volume estimate of excavated masses was sought, as alum shale poses an environmental and health risk due to the decomposition to sulfuric acid by weathering and high uranium content giving radon gas. Preliminary AEM models had a tendency to overestimate the thickness of the very resistive overburden. Experimenting with and optimizing the inversion settings resulted in models better fitting a priori information from the survey area. Limited low moment data were available due to a noisy environment. This affected the reliability of the models, illustrated by modelling and resulting real data models.

Key words: AEM, Time-Domain, Near-Surface, System Response, Geotechnical

INTRODUCTION

Geotechnical AEM plays an increasing role as a highly cost- and time-efficient method to design detailed drilling campaigns (Pfaffhuber et al., 2016). These geotechnical surveys stretch the achievable near-surface resolution as the first five to ten meters have the highest impact on surface infrastructure projects and are often the most difficult to resolve. Encouraging results have been reported, but also pitfalls (Baranwal et al., 2015) depending on the methodology used.

The recently introduced *system response* method applied to SkyTEM data gives the opportunity to utilize the very earliest time gates (before 10 µs), including during the ramp down, and thus ideally achieves even better resolution in the near-surface (Andersen et al., 2016). We test this method on a site where very small resistivity contrasts (5 to 10 Ωm embedded in 10 to 50 Ωm) are crucial to resolve to successfully identify hazardous quick clay. In another setting, we study the stability of AEM models in a setting with extremely high resistivity contrast (100s to 1000s Ωm overlaying 0.1 to 1 Ωm) in combination with a noisy environment.

We find that utilizing the very early time gates increases the near-surface resolution and makes it possible to distinguish and resolve layers with small resistivity contrasts. In a setting with a highly resistive top layer over very conductive shales, giving an extremely high contrast in resistivity, the inversion results become unstable depending on the parameters set in the inversion. The inversion parameters therefore have to carefully be set to suit geological conditions present, in order to obtain reliable models. Lack of low moment (LM) data also makes the models less reliable as information about the near-surface is lost.

METHOD AND RESULTS

As we neither present new instrumentation nor processing schemes in this work but rather analyse the reliability of AEM models under "extreme" conditions, we only briefly outline the method's background:

The AEM data used in this study were acquired with the SkyTEM 304 system (Sørensen and Auken, 2004) with a 341 m^2 frame utilizing both low moment (LM) and high moment (HM) data, with one and four turns respectively. The raw data were processed using Aarhus Workbench (www.aarhusgeosoftware.dk) and inverted using both smooth and layered laterally constrained inversion (LCI) (Auken et al., 2005). When running inversions without system response the range of time windows used is 10 µs to 8.9 ms, while when system response is applied times as early as 0.515 µs is used.

When the very early time responses are modelled, an accurate description of the system is needed. The effect of the transmitter waveform and the filters (receiver coil and electronics) are gathered into a single system response. The system response (SR) is convolved with the theoretical secondary response from the Earth in the forward modelling in the inversion process (Andersen et al., 2016). This method makes it possible to calculate the response for the earliest times and thus ideally give models with better resolution in the near-surface.

Geotechnical borehole data, in our case R-CPT data, was used as a basis to create synthetic models used for comparison with the real AEM models. During an R-CPT measurement, the ground resistivities are measured at the same time as performing a standard cone penetration test (CPT). The sensor consist of four ring electrodes in a Wenner configuration and the sensor is mounted on the CPT probe. The probe is pressed into the ground at a constant velocity and readings are made every second (Sandven et al., 1012). The equipment used in the survey is manufactured by the Swedish company Geotech.

The inversion program AarhusInv was used to conduct the synthetic modelling based on the R-CPT measurements. Synthetic layered models fitting the R-CPT measurements were made. A forward response from each of the synthetic models was generated and used as input in a regular inversion. The data from the synthetic models were both inverted with and without SR. The resulting models based on the synthetic data were then compared to the real AEM data models in the area of the R-CPT.

Quick clay delineation

In an area with conductive sediment over resistive bedrock, system response was tested to investigate if any improvement of the near-surface resolution was obtained. Possible quick clay, which is a highly sensitive marine clay that changes to a liquid if failure occurs, is known to be present in the survey area. Construction projects in quick clay areas are challenging, and knowledge about the conditions and great care is needed to prevent possible disasters (Anschütz et al., 2015). Only small resistivity contrasts distinguish quick clay from normal marine clay. It is therefore of great importance to be able to resolve subtle contrasts in order to detect quick clay units.

With the use of system response (SR), a tendency of more pronounced structures in the near-surface is observed. In some areas, a more resistive layer appears close to the surface in the model section inverted with SR, compared to the inversion result without SR (Figure 1). The resistivity values present in the case inverted with SR could correspond to quick clay, while the models inverted without SR showed lower resistivities in the same area, which could have been interpreted to be normal marine clay. In another section inverted with SR, a shallow layer of about five meters of slightly higher resistivity than the surroundings appears in vicinity of one of the R-CPTs (borehole VSS11002) (Figure 2). A thin more resistive top layer also appears in parts of the profile, which might correspond to dry crust.

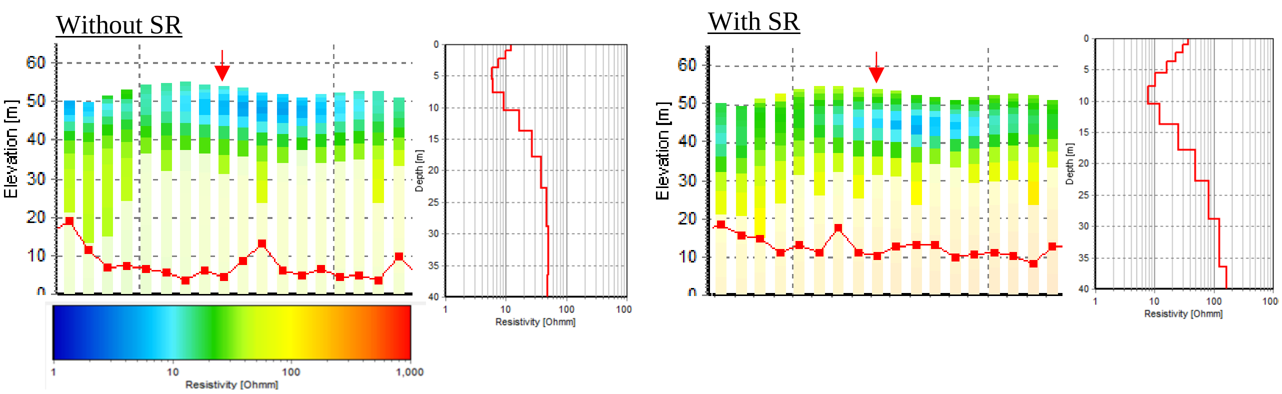

Figure 1: System response applied to real data. Left: Resulting models inverted without SR (first 6 gates omitted in inversion) and resistivity (Ωm) with depth (m) profile at the location of the red arrow. Low resistivities are observed close to the surface. Right: Resulting models inverted with SR (gate 2-6 is included in inversion) and resistivity (Ωm) with depth (m) profile at the location of the red arrow. A layer of slightly higher resistivities is observed close to the surface compared to the inversion result without SR.

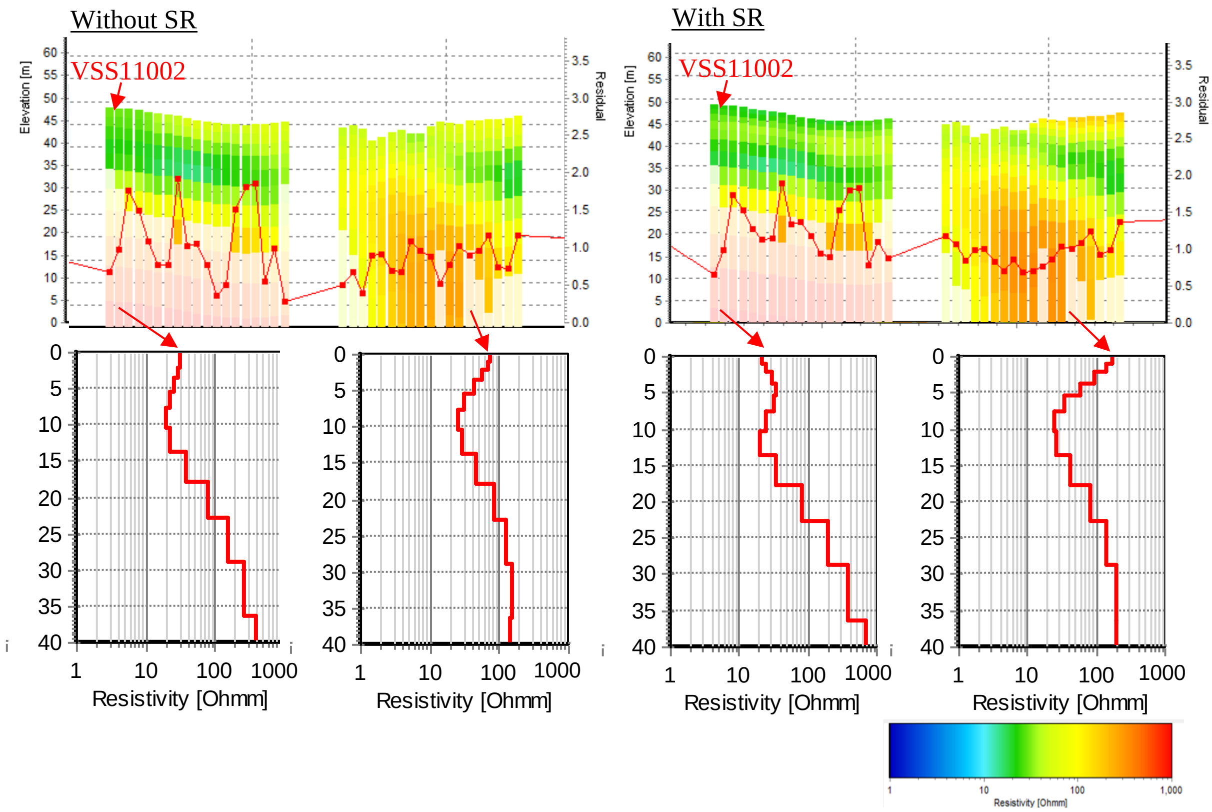

Figure 2: System response applied to real AEM data. Top left: Resulting models inverted without SR (first 6 gates omitted in inversion). Top right: Resulting models inverted with SR (gate 2-6 is included in inversion). Bottom: Profiles giving resistivity (Ωm) with depth (m) inverted without (left) and with (right) SR at two locations along the profile (with the left one in each case at the location of one of the R-CPTs). Location of borehole VSS11002 is marked in profile.

The inversion results from the synthetic modelling, based on an R-CPT measurement in the area (borehole VSS11002), show similar trends as to what was observed in the real data (Figure 3). The R-CPT measurements from the area show a more resistive layer embedded in less resistive masses. In the model inverted with SR this slightly more resistive layer is resolved, while the model inverted without SR is not able to detect this layer. There are striking similarities between observations done in the real data and the synthetic modelling based on the R-CPT. These results indicate that a higher resolution is achieved when inverting with SR and one are capable of detecting subtle resistivity contrast in the upper meters, not possible without the data from the earliest gates. General synthetic modelling with a two-layer model was conducted as well, also showing an improvement of the resolution in the upper meters. The modelling with SR seems to improve the near-surface resolution in areas with smaller resistivity contrasts, while for a larger contrast no difference in the model resolution is observed for inversion with and without SR. The improvements observed with the use of SR are visible in the upper 5-10 meters.

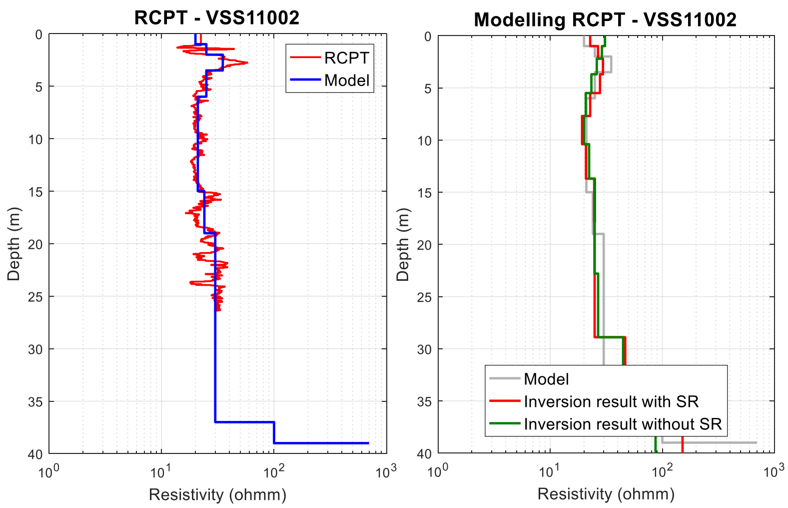

Figure 3: Modelling and inversion results with system response for R-CPT from borehole VSS11002. Left: R-CPT measurements (red) and its synthetic layered model (blue). Right: Inversion results with (red) and without (green) applying SR where synthetic data from the created model were used, together with the synthetic model based on the R-CPT measurement (grey).

Depth to black shale

In an area with very conductive black shales covered by rather resistive sediments of variable thickness, the depth to the conductive masses was expected to be an easy target. It turned out that finding the correct depth was challenging, and the preliminary AEM models tended to overestimate the thickness of the resistive top layer. We were interested in investigating the reason for the unexpected result and if a better model could be obtained by experimenting with the inversion settings. There were limited good quality LM data available due to a strong noise environment, resulting in large areas where only HM data were available. This also affects the resulting models, and modelling was conducted in order to get an understanding of the importance of having LM data for the result. Both the geological setting and the limited LM data coverage made this a challenging dataset to work with.

The experimentation with inversion parameters showed that the parameters set for altitude inversion and start resistivity were of significant importance and had a great impact on the appearance of the inverted models. Depending on the start resistivity the inverted altitude was over/under estimated in areas with thicker resistive masses giving a too thin/thick and less/more resistive top layer. The flight altitude was therefore tightly constrained to follow the measured altitude. Also vertical and horizontal constraints were set to be looser to allow for larger contrasts, as it was known that there was a sharp vertical contrast between the layers as well as quick lateral variations. Carefully choosing the inversion parameters to suit the geological setting present, resulted in models better fitting other geological and geotechnical information available from the survey area (Figure 4). Comparing the model result from inversion with just HM data and inversion with both HM and LM data show the importance of having LM data for the result. The models in the areas where LM data were present give a more reliable result in terms of resistivity values and the depth to the shale layer (Figure 4).

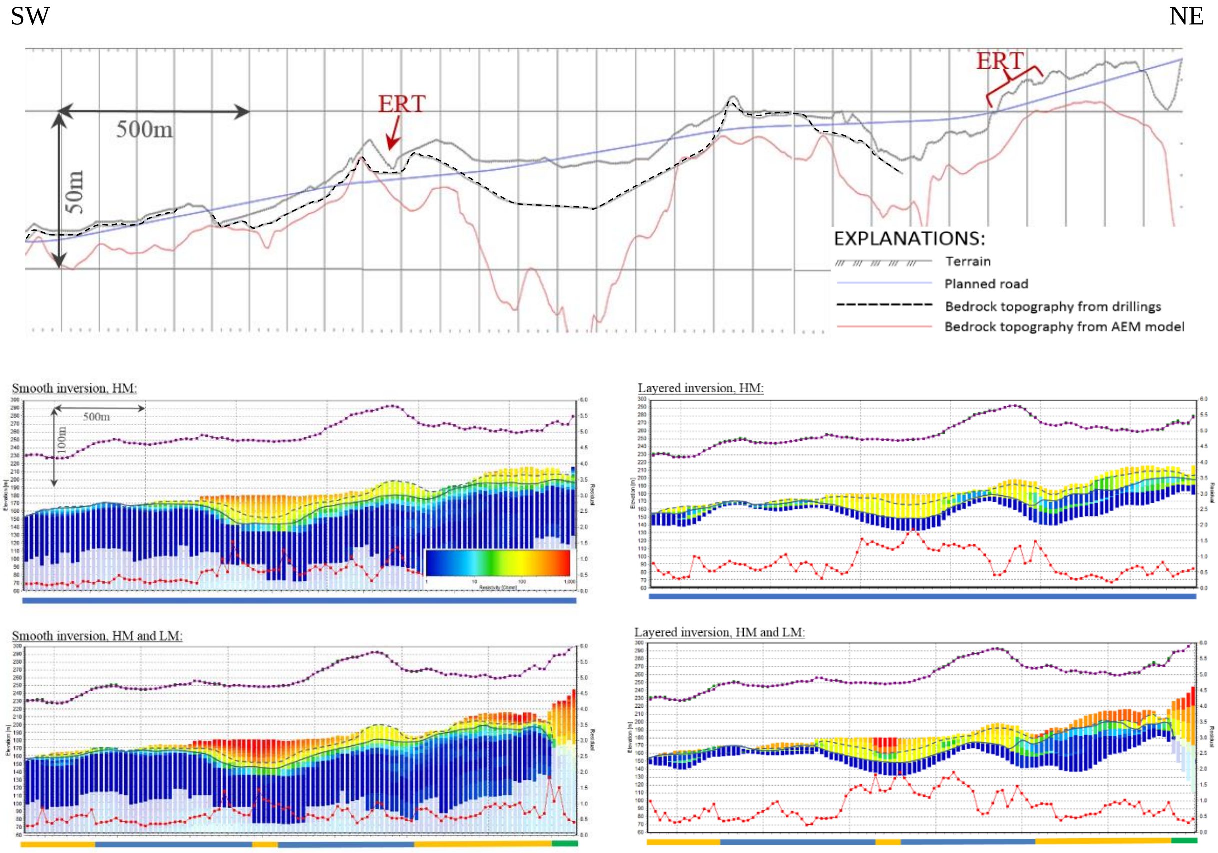

Figure 4: Comparison of interpreted depth to bedrock along the planned road and the final AEM resistivity models. Top: Profile along the planned road with bedrock topography based on drillings (stippled black line) and preliminary AEM model (red line), and planned road alignment (blue line). Bottom: Smooth (left) and layered (right) inversion results inverted with HM data (top) and with HM and LM data (bottom). Red line gives the data residual, purple line is flight altitude. Colour code below the profiles gives the presence of HM and LM data along the flight line; blue=HM, green=LM, orange=HM and LM. The stippled and solid line give a lower and upper manually interpreted depth to bedrock respectively. All profiles are oriented from southwest to northeast.

Synthetic modelling was performed based on geotechnical borehole data and resistivity values from ERT data from the survey area. These models showed the importance of having LM data to get resistivity values closer to the reality and to be able to detect boundaries more accurate (Figure 5). Only having HM data tended to give too low resistivity values in the top layer and a less pronounced and deeper boundary. This is similar observations as done in the real data models (Figure 4).

CONCLUSIONS

Both applying SR in the inversion of real AEM data and to synthetic data shows to provide increased near-surface resolution of the models. This could be of great importance in eg. geotechnical projects where applying SR could make it possible to distinguish small resistivity contrast as for marine clay and quick clay. Our results also demonstrate the large impact the inversion settings set have on the result and the importance of adjusting the inversion settings to suit the geological setting present, in order to get reliable results. LM data is needed to get a good representation of the conditions in the upper meters in the subsurface.

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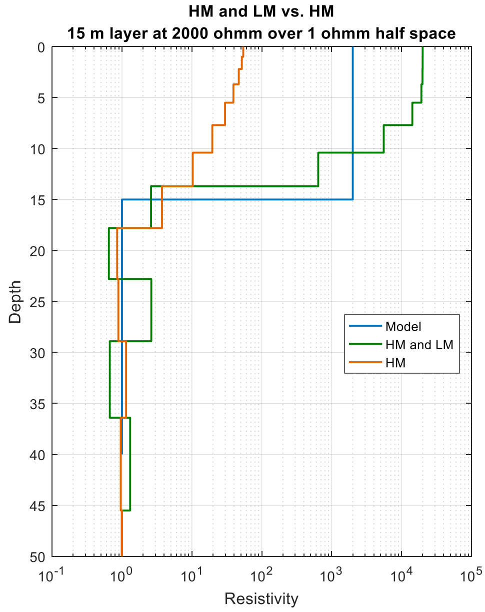

Figure 5: Smooth inversion result from modelling of 15-meter layer of 2000 Ωm over 1 Ωm half space with just HM data (orange) and with HM and LM data (green). Blue line is true model based on thicknesses from borehole data and resistivity values from ERT data. Start resistivity = 200 Ωm and flight altitude not included as an inversion parameter.

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