Airborne geoscanning as a site investigation tool in large-scale tunnelling projects: A synthesis of case studies from Norway and India

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Abstract. Unforeseen, challenging ground conditions are a major obstacle for infrastructure development, including tunnel construction. Addressing this risk with traditional, intrusive ground investigations can be costly, sometime prohibitively so. In this paper, we present airborne geoscanning, a more efficient site investigation method that integrates airborne geophysics with other datasets to produce ground models. We primarily employ helicopter-based time-domain electromagnetics (AEM), a method that images differences in electrical resistivity in the subsurface. When available, we can combine geophysical data with ancillary datasets for more sophisticated interpretation, an integrated process we call airborne geoscanning. Integration techniques range from simple clustering analysis that support planning of follow-up ground investigations to customised artificial neural networks that automatically detect interfaces like top of rock. Using examples from projects in Norway and India, we illustrate the strengths and weaknesses of using airborne geophysics for tunnelling projects. Using these case studies, we demonstrate three key insights that airborne geoscanning can provide to tunnelling engineers: identify major fractured zones, weaker rock units and rock cover. These insights can be highly valuable for tunnel design and construction projects worldwide.

1. Introduction
Unforeseen, challenging ground conditions are a major obstacle for infrastructure development, including tunnel construction. They are one of the major reasons why 90% of transportation infrastructure projects globally exceed their budgeted cost and why tunnelling project on average exceed their expected costs by 50% [1]. While traditional borehole investigation techniques help mitigate uncertainty in ground conditions, they can be costly, time-consuming, and provide only sparse, discontinuous information. Rugged terrain or remote locations can sometimes make it impossible to collect borehole data.

Using indirect investigation methods like airborne geophysics presents an opportunity to gain early insights in large tunneling projects. Specifically, airborne electromagnetics (AEM) is a technology originally from the mining industry that has increasingly been used for engineering applications in tunneling [2,3,4]. This development started about 10 years ago but has been used increasingly within the last 3-5 years. Though indirect and less precise than intrusive ground investigations, AEM surveys allow one to acquire continuous data over a large area, and they give key insights about the ground...
conditions early in the planning and design of large tunnels. Moreover, AEM data can be used throughout the lifetime of the project by integrating them with other geotechnical data to generate better ground models in a process we refer to as *airborne geoscanning*.

To demonstrate the utility of airborne geoscanning, we synthesize four case stories of tunneling projects in Norway and India. The first three of these are previously unpublished, and we summarize results from a fourth project first published in [5]. In these examples, the method was used to map major fracture zones, units of weaker rock, and to map the depth of rock cover over a tunnel. In many cases, these results were invaluable for efficiently planning follow-up investigations, and for optimizing tunnel designs and alignments much earlier in the project than what would have been possible using intrusive ground investigations alone. This is the first multi-national, tunneling-specific review of airborne geoscanning in the literature that we know of. The comparison of outcomes across contrasting geological environments will be of interest to readers, as will the novel application of machine-learning interpretation in some of these case studies.

2. Methods

2.1. Airborne electromagnetics (AEM)

AEM surveys, used as the basis for the case studies described below, were all acquired by helicopter. Flown at low elevations (30 – 150 m above ground), they can rapidly collect high-resolution geophysical data. Data are collected along the planned alignments and on near-parallel lines surrounding this, commonly between 75 – 200 m apart, providing a unified overview of the ground conditions. The electromagnetic data is used to produce 3D resistivity models, from which different geological circumstances can be interpreted due to their associated resistivities.

In the time domain electromagnetic (TEM) instrumentation a time-varying current is transmitted in a coil and creates an electromagnetic field [6]. In turn this field induces eddy currents in the ground that diffuses down- and outwards with time after the transmitter current is switched off. To measure the resulting secondary magnetic field early after the primary current is switched off means that the shallow depth of the ground can be investigated. Later time gates will give information about deeper parts. In this way it is possible to gain information down to a depth of 400-800 m depending on instrumentation setup, system used and geology of the area.

2.2. Interpretation methods

We use several methods to interpret resistivity models depending on project needs and the availability of supporting data. The three that we cover in this paper, in order of increasing complexity and automation, are isovolume analysis, clustering, and AI-based interface detection. Isovolume analysis is employed where ground-truth data is limited and where the 3D geometry of rock units is particularly important for a project. Based on either a histogram of resistivity distributions or on an inspection of overlapping borehole logs, an expert selects representative resistivity intervals and extracts isovolumes from the 3D resistivity grid. Visualizing these volumes alongside planned tunnels allows one to optimize alignments such that weak zones or undesirable rock units, which often tend to have lower resistivities, may be avoided.

Clustering analysis is most for planning follow-up ground investigations following an AEM survey. This technique groups together locations at surface with similar vertical resistivity profiles, allowing one to quickly assess the heterogeneity of an area and subsequently gather a stratified, unbiased sample of the geology of the area with subsequent geotechnical drillings.

When a particular boundary or surface is the target of an investigation, we employ an automated AI-based interface detection algorithm. This algorithm uses observations of an interface from outcrops, drillings, excavations, etc. as training data, then feeds the spatial coordinates and AEM-based resistivity models to an artificial neural network (ANN) that predicts the depth to this interface [7]. Where ground-truth data are not available, manual interpretation points may be used as training data.
instead. This technique is often used for detecting the bedrock-sediment interface (i.e., depth of cover) [8] but also for detecting any interface with a resistivity contrast, such as the bottom of peat [9].

3. Results

3.1. Identifying of major fracture zones (Norway)
The FRE16 project (Norwegian: Fellesprosjekt Ringerikshansen E16) is a joint railway and highway design project, located in a forested area, launched in 2015. The goal is to connect the city of Sandvika, which borders Norway’s capital Oslo, and the city of Hønefoss with 40 km of new rails and roads. This plan includes a 23 km railway tunnel in the southern half of the project. 655 line-km of AEM data were collected in June 2016 (Figure 1A).

Results from the geophysical surveys indicated that the planned tunnel alignment intersected largely high-resistivity (and presumably strong) rock. However, the tunnel intersects a major, low-resistivity unit near its northern portal (Figure 1B). Later core drillings confirmed that this resistivity unit coincided with a transition from igneous rocks (rhomb-porphry, basalt) to sedimentary rocks (sandstone, siltstone, mudstone), as well as a decrease in drilling resistance (Figure 1B) and a decrease in Rock Quality Designation (RQD) (Figure 1C). This feature persists perpendicular to the alignment of the tunnel (Figure 1C), so this unit cannot be avoided by a minor alignment adjustment.

![Figure 1](image.png)

**Figure 1.** A zone of weaker, more fractured rock detected by AEM and confirmed by a core drilling (BH25): (a) location of the AEM survey and the example boreholes; (b) a vertical section; (c) a 3D oblique view showing a low-resistivity unit. Tunnel alignment shown in fuchsia. Vertical exaggeration of 3x used.

There is another unit of low-resistivity rock that is subparallel to the tunnel alignment. This coincides with a narrow valley at surface, suggesting that this is a fault zone. Fortunately, the proposed alignment does not intersect this unit of low-resistivity material.

3.2. Mapping weak rock units (India)
Recently, airborne geoscaning was employed in two high-elevation road tunnel projects in northern India. The first, 6.5 km-long tunnel is currently being excavated, whereas the second, 14 km-long tunnel is still in the planning and design phase. Geoscaning was undertaken in the first case primarily as a demonstration and verification of the method, whereas in the second case, it was used to support ongoing ground investigations wherein ground-truth data are sparse. At both sites, bedrock consists of low- to medium-grade metamorphic rocks. The Zojila Formation (slate, schist, and phyllite) and Panjal Trap Formation (metabasite) occur at both sites, and Agglomerative Slates (slate) are also mapped at the second site. In both cases, the primary application of geoscaning was to map the occurrence of weak, phyllitic rock.
3.2.1. Example 1: Results of the geoscanning revealed that the central portions of the tunnel consist of mainly very high-resistivity rock (>1000 Ωm) whereas the portal areas contain of either medium (100-400 Ωm) or low resistivity rock (< 50 Ωm). The low resistivity zones correlated well with the major shear zones detected near the boundaries between the Zojila and Panjal Trap Formations. The high resistivity units detected in the central part of the tunnel corresponded with the stronger rocks of the Panjal Trap Formation. A direct comparison of resistivities and geotechnical cross sections was not possible in some central parts of the tunnel (chainage 9000 m) because the helicopter could not fly directly above the tunnel due to very steep terrain.

These correlations are apparent both in map view and in cross-sectional view (Figure 2). In addition, a near-surface transition from higher to lower resistivities is visible in some areas and appears to correlate well with the expected water table in the area. The results also agree with observations made by geologists on site. In the western and eastern portal areas weak rock was detected during the blasting process, slowing down the progress of construction. In contrast, excavation in the central part of the tunnel detected good quality rock.

![Figure 2](image.png)

**Figure 2.** (a) Geological map of the area, prepared by [10]; (b) Slice of the AEM-derived resistivity model at a depth of 200 m below terrain; (c) geological cross section along the tunnel alignment adapted from [11]; (d) Resistivity along the section.

3.2.2. Example 2) Given that at the first site, low- and high-resistivity rock corresponded to weak and strong rock, respectively, we visualized low and high-resistivity units as a proxy for zones of strong and weak rock. Specifically, we visualized volumes of material with >1000 Ωm and < 100 Ωm alongside the tunnel alignment in 3D. We identified four units of high-resistivity (A, B, C and D) and four of low-resistivity (Q, R and S) (Figure 3).

By visualizing these units alongside the planned tunnel alignment in 3D, we see the alignment appears to have a suitable horizontal placement. For instance, to the west, between a chainage of 5 to 7 km, the tunnel avoids low-resistivity unit R, which is more likely to be weak rock. However, some adjustments to the vertical alignments might be warranted. The tunnel is positioned near the lower limit of Unit B and Unit C. Raising the elevation of the tunnel slightly may prove advantageous to avoid deep, low-resistivity rock units.

3.3. Tunnel rock cover (Norway)
Planning of a new 19-km stretch of double-lane highway about 30 km northeast of Trondheim, Norway began in early 2019 (Figure 4). In this area, bedrock depth was highly variable, ranging from
outcropping at surface to buried below tens of meters of soft clay, posing significant engineering challenges for planning a road alignment. Few boreholes had previously been collected in the area. Engineers predicted that 600 geotechnical boreholes would have to be drilled to sufficiently reduce the geological uncertainty in the wide corridor, but they chose also to utilize airborne geoscanning in June 2019 before the first major drilling campaign [12].

Results from a cluster analysis of the geophysical data was used as input for planning the first major drilling campaign. Analysts interpreted the resulting four clusters (Figure 4a) as corresponding to: Deep sediments, Shallower sediments, Outcropping rock, and Very deep sediments. Comparing the distribution of cluster membership of the geophysical model (Figure 4b) versus the borehole data (Figure 4c), it was found that for distribution of boreholes, areas with Very deep sediments were undersampled compared to areas with Deep sediments while areas with Shallow sediments were oversampled by the borehole data. Also note that Outcropping rock is undersampled by boreholes as these can be evaluated on the surface. This assessment helped the engineers to appropriately prioritize drilling areas with anomalously deep bedrock.

Figure 3. (a) 3D view of the resistivity model, showing the tunnel alignment (white line), resistivity volumes >1000 Ωm (yellow) and <100 Ωm (dark purple); (b) Map of the maximum extends of the high-resistivity Units A and B and low resistivity unit R; (c) Cross section of the resistivity model and planned tunnel.
A top of rock model was generated and updated using the ANN-based method described in 2.2. A first version was generated a few days after the collection of geophysical data and subsequently updated many times after each major geotechnical drilling campaign. Even the first version of the bedrock model, which utilized only the sparse, pre-existing drillings, pointed to two locations where there was a lack of rock cover even though sufficient rock cover had been assumed: Fossingelva and Grubbåsen (Figure 5).

At Grubbåsen (Figure 5a), the first geoscanning-based bedrock model was 10 m deeper than expected and was close to the tunnel ceiling. Engineers thus focused follow-up borehole investigations at this location, and a deep, narrow depression was discovered in the bedrock surface that intersected the tunnel profile. At this location, there was no flexibility to change the tunnel alignment, so the tunnel support design, construction plans and project budgets were revised to account for these challenging ground conditions [5].

Similarly, at Fossingelva (Figure 5b), rock cover above the planned tunnel location was virtually nil according to the first interpretation of the geophysical data, prompting the planners to move the tunnel some hundreds of meters west and to focus follow-up drillings at the new location. An updated model indicated only 5 m of rock cover at some sites on this new location, so the tunnel was ultimately repositioned to 50 m deeper.
4. Discussion

Beyond illustrating what sort of subsurface structures that airborne geoscaning can identify, the four case studies herein demonstrate the major value-adding potential this method has for large tunneling projects, especially in early phases. This is because the method can quickly identify areas with unfavorable ground conditions. Another large benefit of the method is the ability to collect data in areas which are densely forested (3.1), covered by snow, or with limited access (3.2). The example from central Norway (3.3) demonstrates this first point concretely, where the initial alignment proposal at Fossingelva was discarded and adjusted soon after the geoscaning survey. This decision ultimately led to direct cost savings in the project because an estimated 30% fewer drillings and three months less of planning time were ultimately needed [12]. When poor ground conditions cannot be avoided, a more precise determination of construction costs and geological risks are still valuable, as the examples from Grubbåsen (3.3) and Ringeriksbanen (3.1) demonstrate.

Even when results of geoscaning are less certain, identifying major geological changes or risky zones helps increase the efficiency of subsequent ground investigation. The case studies from India (3.2) demonstrates this point. Though the correlation between resistivity and rock strength is less precise, results point to locations in Example 2 that should be further investigated where the tunnel encounters change in resistivity. Knowing the extent of each rock unit can also potentially help engineers avoid drilling excess holes in rocks that lie in the same contiguous resistivity unit and that are more likely to have similar properties. Likewise, at Grubbåsen in central Norway (3.3) one can argue that although the first geoscaning-based bedrock model did not precisely capture the finer details of that narrow depression (Figure 5), the model did correctly point to a potentially risky zone warranting more drillings.

The case studies presented contrast in how much ground truth data was available for detailed, quantitative interpretation. In the Indian examples (3.2), boreholes are especially difficult to acquire due to the remoteness of these locations and due to rugged, challenging terrain. Though some sparse, drill core data was previously collected in these sites, this may not be possible for all tunneling projects. The results shown highlight the value of using airborne geophysics in remote locations. Yet, even where a large quantity of supplementary geotechnical data is available, as they were in central Norway (3.3), integrating these data using advanced methods like ANN unlocked extra value in both datasets.

There are limitations, however, in the applicability of airborne geoscaning. Some of these are logistical, such as the accessibility of survey area. While helicopter-based methods can cover many areas that ground-based geophysics cannot, as the first Indian example shows (3.2.1), it was not
possible for the helicopter to maneuver over the steepest part of the mountain ridge above the tunnel. Urban areas are for safety reasons not accessible to helicopter-based investigations and roughly 100 m distance to existing (metallic) infrastructure must be kept to extract geological models from electromagnetic measurements.

Some limitations also arise from the geophysical method. The geophysical contrast between a target structure and its surrounding must be strong enough for it to be detected by an instrument. For instance, though we detected a major weakness zone in 3.1, there are conceivably very thin fractures or zones that are significant for tunneling engineers but that are not large enough to be imaged by airborne geoscanning. The resolution of the geophysical instrument is also a limitation. This particular helicopter-based time-domain instrument usually have vertical resolutions of some metres in the near-surface, and only tens of metres at some hundred metres of depth. Similarly, lateral resolution is generally 30-100 m depending on depth and on the height of the instrument above ground. Integrating ground truth data with geophysical data still allows one to create geological models that are accurate to within some metres. Both the case study from central Norway (3.3) as well as previous back-analysis of past geoscanning projects [8] are evidence to this.

Despite these weaknesses, the case studies herein clearly indicate that large cost-savings in large-scale infrastructure projects are possible in a variety of geological environments worldwide. While airborne geoscanning cannot completely eliminate geological risk, the early-phase, broad insights that it provides contribute greatly to the reduction of such risk.

5. Conclusion
Using geoscanning in early or late-stage phases of tunnelling projects, ensures that valuable insight into study areas can reveal potential zones for follow-up investigations. The four case studies presented here have shown the possibility to detect major fracture zones, weak rock units, and insufficient rock cover. This led to better planning of drilling campaigns and earlier optimizations and re-design tunnel alignments and tunnel support design. By having the opportunity to address these issues early in the planning phase before large investments have been incurred reduces the risk of cost overruns. Even when projects are in a later stage or tunnel alignment modifications cannot be avoided, a more precise estimation of costs and geological risks are still valuable for ensuring financially sound and safe construction.

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We dedicate this paper to the memory of Mr. Sanjeev Malik who went to his heavenly abode due to COVID-19 during the preparation of the manuscript. Mr. Malik, Executive Director of India’s National Highways and Infrastructure Development Corporation Ltd, was forward thinking with a keen interest in EM methods and the possibilities to use data in large infrastructure projects. We know Mr. Malik as a very intelligent, pleasant, and kind man. He will be sorely missed, and the loss is felt heavily by all.

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References
[1] Beekers F, Chiara N, Flesch A, Maly J, Silva E and Stegemann U 2013 A risk-management approach to a successful infrastructure project. McKinsey Working Papers on Risk 52
[2] Pfaffhuber AA, Grimstad E, Domaas U, Auken E, Foged N and Halkjaer M 2010 Air-borne EM mapping of rockslides and tunneling hazards. Lead. Edge 29 8 956–959
[3] Okazaki K, Mogi T, Utsugi M, Ito Y, Kunishima H, Yamazaki T, Takahashi Y, Hashimoto T, Yumamaya Y, Ito H, et al. 2011 Airborne electromagnetic and magnetic surveys for long tunnel construction design. Phys. Chem. Earth 36 1237–1246
[4] Pfaffhuber AA, Lysdahl A O K, Sørmo E, Skuradal G H, Thomassen T, Anschütz H, and
[5] Harrison EJ, Skurdal GH, Christensen CW, Pfaffhuber AA, Lund AK, and Second B 2021 Applying machine learning on airborne geophysical models to map bedrock topography and its lithological boundaries. ITA-AITES World Tunnel Congress, WTC2022 and 47th General Assembly Bella Center, 22-28 April 2022, Copenhagen [In Review]

[6] Christiansen A V, Auken E and Sørensen K 2009 Groundwater Geophysics 2nd, ed R Kirsch (Berlin: Springer) pp 179-226

[7] Lysdahl A K, Andresen L and Vøge M 2018 Construction of bedrock topography from airborne-EM data by artificial neural network. 9th European Conf. on Numerical Methods in Geotechnical Engineering (NMGE 2018), 25-27 June 2018, Porto. Extended Abstract

[8] Pfaffhuber A A, Lysdahl A O, Christensen C, Vøge M, Kjennbakken H and Mykland J 2019 Large scale, efficient geotechnical soil investigations applying machine learning on airborne geophysical models. Proc. of the XVII European Conf. on Soil Mechanics and Geotechnical Engineering, 1-6 September 2019, Reykjavik

[9] Silvestri S, Christensen CW, Lysdahl AOK, Anschütz H, Pfaffhuber AA and Viezzoli A 2019 Peatland volume mapping over resistive substrates with airborne electromagnetic technology. Geophys. Res. Lett. 46 6459–6468. https://doi.org/10.1029/2019GL083025

[10] Grusamar Ingeniería y Consulting 2017 Z Morh Tunnel Geological Plan Layout with Geotechnical Investigation. Drawing no. DNDA/ADV/1029-Z MORH/2017/5_1, DNDA/ADV/1029-Z MORH/2017/5_2

[11] Grusamar Ingeniería y Consulting 2017 Z Morh Tunnel Geotechnical Longitudinal Profile. Drawing no. DNDA/ADV/1029-Z MORH/2017/6_2, DNDA/ADV/1029-Z MORH/2017/6_3

[12] Christensen CW, Skurdal GH, Pfaffhuber AA, Rønning S, Lindgard A and Sellgren KC 2020 Airborne geoscanning and efficient geotechnical ground investigation workflows: A road-building case study from Central Norway. 18th NGM Nordic Geotechnical Meeting – Virtual Conf., 18-19 January 2021, Helsinki. Extended Abstract