Minimal-Impact Site Characterisation To Support Infrastructure Development

R. D. Eddies
Fugro, Savoie Technolac, 34 allée du Lac d'Aiguebelette, 73375, Le Bourget-du-Lac Cedex, France, r.eddies@fugro.com

D. Kilcoyne, B. Barnwell
Fugro, Fugro House, Hithercroft Rd, Wallingford, Oxfordshire, OX10 9RB, United Kingdom

C. Duvail, L. Baudouy
Fugro, 115 avenue de la Capelado, 34160 Castries, France

L. Metral
Fugro, Savoie Technolac, 34 allée du Lac d'Aiguebelette, 73375, Le Bourget-du-Lac Cedex, France,

ABSTRACT: The migration of geophysical technologies and knowledge originating from the hydrocarbon exploration sector has opened up possibilities for light-footprint, unobtrusive approaches to site characterisation for major infrastructure development. We present a case study relating to one of Europe's largest tunneling programmes associated with potash mining. Complex technical and stakeholder challenges and environmental constraints were overcome by wireless seismic acquisition technologies coupled with environmentally benign sources as part of an integrated site characterisation programme. Additionally, relatively rapid, light-footprint capture of the complete seismic wavefield through broadband seismic technologies and passive imaging techniques offer significant future promise for more robust representation of the ground.

Keywords: seismic; low-impact, site characterisation, tunnels

1. Introduction

Geospatial, geological, geophysical, geotechnical and geohazard data (collectively, 'Geo-Data') are required to develop a high-fidelity representation of the ground conditions as part of the site characterisation process. Without such a representation of in-situ conditions, owners, designers and constructors are exposed to the consequences of unforeseen but likely foreseeable ground conditions. Poorly defined subsurface conditions leave the way open for inadequate or inappropriate design on the one hand leading to overengineering and economic waste and on the other hand increased and unacceptable risk of failure, construction claims and a potential legacy of issues during operation including loss of public support, large insurance claims and other costs, all resulting in reduced return on investment from that expected [1].

Civil engineering Geo-Data serves three primary purposes centered on design, pricing and quality (Table 1):

Table 1: The primary purposes of Geo-Data for construction projects [1]

Purpose of Geo-Data		Description
Design		Geo-Data inform engineering design – the objective being to develop safe and economic construction
Construction Pricing		Geo-Data inform the pricing of the construction by the contractor and the avoidance of exorbitant pricing of the management of ground risk
Quality		Geo-Data confirm that engineering objectives have been met in construction – this is particularly important for urban projects where construction can have considerable effect on adjacent facilities

For geophysical characterisation of the ground, a number of technological developments in seismic exploration are now readily migrated to the engineering sector for improved site characterisation of major infrastructure including, for example, tunnels and nuclear sites. Key technical developments include point seismic receiver acquisition [2], cable-free seismic receiver spreads [3] MEMS broadband receiver technology [4] and a spectrum of lightweight vibroseis technologies [5].

In this paper we demonstrate how a number of such technologies are improving site characterisation outcomes for infrastructure development.

2. Preconstruction Geophysical Screening: Overview

A predictive ground model approach [6] is a means to achieve uncertainty reduction and preventative ground risk management through iterative data addition (from integrated site characterisation activities) constrained by geological expertise and knowledge.

To populate the initial ground model space for infrastructure development and to overcome uncertainties in the description of physical properties determined from a few direct sample points only (the traditional boreholes approach), geophysical screening through early engagement with specialist practitioners and experienced consultants is increasing. Modern engineering geophysics allows wider spacing of intrusive investigations to be adopted where ground conditions appear to be relatively uniform, and justifies more closely spaced, targeted intrusive investigations where they are indicated to be complex and critical [7]. In addition, recent advances in borehole geophysics and wireline logging can provide vital in situ parameters for design.

When adopted as a complementary technique to borehole drilling, the resulting reduced number of boreholes, samples and laboratory testing often means that a more reliable ground model (from a much greater quantity of site data) can be developed for a similar or indeed lower cost to a conventional borehole programme. Following site screening using geophysics, an intrusive programme can then be targeted to effectively characterise the site at the right cost.

In many circumstances, this not only means that the number of boreholes is reduced (with commensurate benefits to schedule, cost and risk), or at least better distributed with the value of each borehole being increased by being located better, but also leads to an intrinsically better ground model. In turn, detailed information from boreholes can then be used to calibrate the geophysical information and allows constrained interpolation between points of control, further improving the ground model and enabling better design decisions to be made.

3. Case Study: Wireless Technology and Low-Impact Vibroseis for Tunnel Route Characterisation

Tunnels are frequently located below areas of multiple land ownership involving complex stakeholder relationships and environmental sensitivities. In this scenario, wireless seismic technology recently migrated from the exploration to the engineering sector avoids the use of cables, making surface obstacles, such as buildings and road and river crossings, much easier to manage, as well as lowering the overall environmental footprint.

Several geophysical screening technologies deployed from the surface are highly suited to investigating tunnel developments as they are operationally efficient when deployed in linear surface profiling mode, (see, for example [8]), all of which can be extended from two dimensions (depth, major tunnel axis) to three (depth, major and minor tunnel axes) where objectives dictate.

We present a case study as an example of how geophysical screening can significantly contribute to the initial predictive ground model and provide valuable insight into subsurface conditions for owners, designers and constructors participating in a major UK tunneling project.

Combined with non-explosive, low-impact vibroseis technology as a seismic source, wireless receiver technology was a key factor in building a predictive ground model for the North Yorkshire Polyhalite Project (Sirius Minerals) in the UK involving a 37-kilometre-long mineral transportation tunnel (Figure 1) partly routed below the sensitive environment of the North York Moors National Park.

The Redcar Mudstone Formation (ReM) [9, 10, 11] within the Cleveland Basin is roughly 250 m thick and provides a continuous stratigraphic unit within which the proposed tunnel could be constructed. The ReM comprises a dominantly mudstone and siltstone lithology with subordinate sandy, calcareous and sideritic nodular or tabular horizons. Surface faulting is observed in the area with a regional NNW-SSE and WNW-ESE trend.

The objectives of the investigation were to accurately highlight the upper and lower contact of the ReM and to determine the possible presence of faults/ fault zones within the tunneling interval that could negatively impact tunnel (TBM) and shaft excavations. Deep drilling to locate faulting at such depths without initial screening of faulting would be uneconomical. Furthermore, areas within the National Park were inaccessible for deep drilling operations. information and allows constrained interpolation between points of control, further improving the ground model and enabling better design decisions to be made.

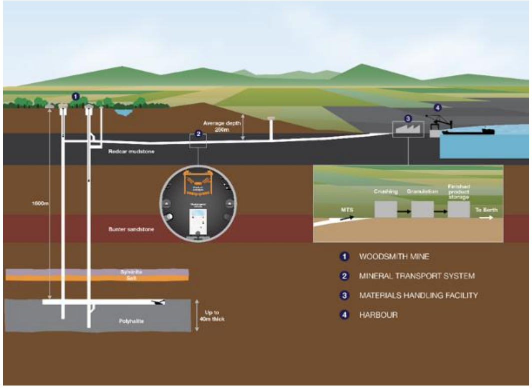


Figure 1: Schematic design for 37-kilometre-long mineral transportation system. Image with permission of Sirius Minerals.

An initial conceptual model (Figure 2), based on British Geological Survey (BGS) surface mapping and existing deep exploration seismic data highlighted the presence of faulting but with only conjectural information relating to the tunneling interval. With tunnel depths exceeding 300 m and being an established technique to detect and define faulting, seismic reflection profiling was chosen as the primary investigative technique for geophysical screening of the route.

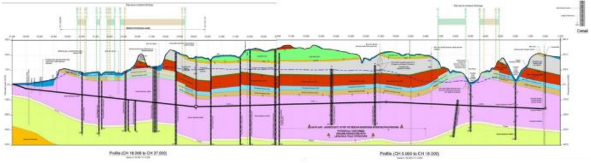


Figure 2: Initial Ground Model for the MTS tunnel route largely based on British Geological Survey information. Note the presence of largely vertical faults throughout. (ARUP, image with permission of Sirius Minerals).

Approximately 80 km of seismic data (Figure **3**) were acquired in 2017/2018 by Fugro as part of the tunnel route screening process, along discrete profiles generally following roads, tracks and fields.

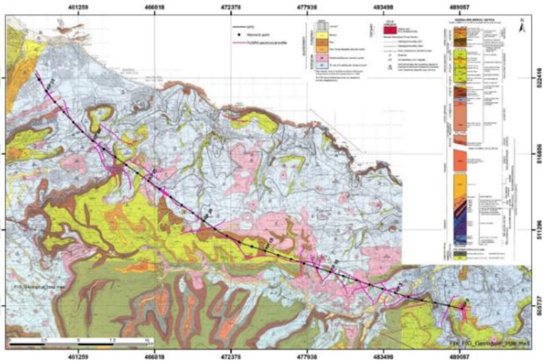


Figure 3: Sirius Minerals MTS tunnel route alignment and underlying geology; seismic reflection profiles in pink. Following a direct route along the tunnel alignment was not feasible for the seismic investigation, survey lines were planned along tracks and roads so as to provide quasi-continuous coverage along the tunnel route with minimum disruption to local communities. Geological mapping information courtesy of the British Geological Survey.

Figure 4: Wireless seismic receivers capture the transmitted signal from a vibroseis seismic source reflected from the subsurface to yield seismic reflection imagery. The combination of these technologies provided a low environmental impact approach for the tunnel investigation and minimal disruption to local communities. An equivalent investigation based on a traditional explosives approach could have involved about 17000 shot holes and up to 10 t of explosives.

A low-impact, highly maneuverable vibroseis seismic source, similar to a medium-sized agricultural tractor (Figure 4) eliminated the need for explosives (estimated at about 10 t) for more than 98% of the route. The vibroseis is an example of a low energy density source that is activated over a long time period (swept frequency) as compared to a high energy source such as dynamite that is activated over a short period (impulsive). The vibroseis provided sufficient power for imaging from the near surface down to more than 1.5 km to provide continuous overlap with existing exploration seismic data publicly available and to obtain deep structural geological information to better understand likely conditions at the tunneling interval. Wireless seismic receivers (cable-free) were deployed along the route every 5 m (Figure 4) and ‘shots’ were acquired between each receiver to yield a maximum fold of 100 (100 x oversampling of each subsurface reflection zone). The combined use of these technologies yielded a very small footprint approach with small field crew sizes (6 field staff) and minimal impact on the environment and surrounding communities (e.g. and allowed seismic acquisition overnight.

Following data processing and conversion from time to depth from a check shot seismic survey, seismic data were interpreted with a specific focus on identifying structure, discontinuities and zones of disturbance within the tunneling interval. Considering the interpreted fault distribution, deformation zones were identified where the geometry of reflectors was disturbed - likely due to faulting/fracturing. These zones were characterised by dip variations and breaks in the reflectors (Figure 5a). Zones where the reflectors appear to be well defined but with clear dip variations were also considered as likely deformation zones despite the absence of obvious discontinuities (Figure 5b).

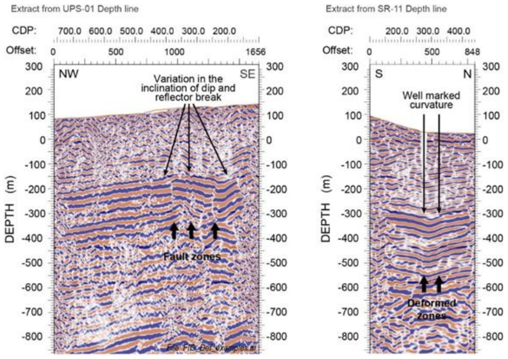


Figure 5: a) example of fault zone (deformation zone) based on dip variations and reflector discontinuities and b) example of dip variations but with no evidence of reflector breaks or discontinuities. Images with permission of Sirius Minerals.

The base of the ReM was evident as a seismic marker horizon present along the complete route. The route was then zoned into three classes: no evidence of deformation within the ReM at the tunnel horizon, evidence of minor deformation and evidence of significant deformation (Figure 6).

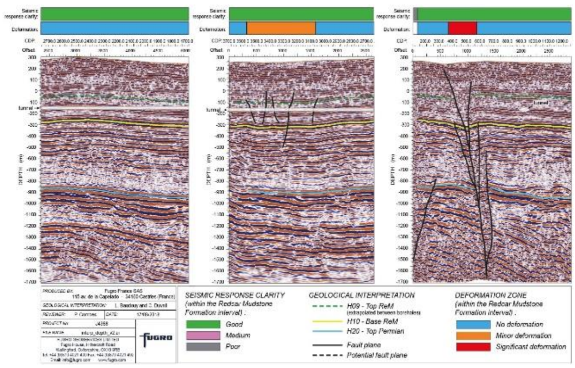


Figure 6: Preconstruction geophysical screening can be invaluable in helping manage risks of TBM operations by confirming the relative position of potentially challenging geological conditions such as fault zones as interpreted above from seismic data. Marker horizon in yellow is the base of the unit hosting the future planned tunnel (Redcar Mudstone Formation). The interpreted seismic data examples show no evidence of deformation (left), evidence of minor deformation (centre) and significant deformation (right) corresponding to similar deep-seated features identified in legacy seismic exploration data. Significant deformation at the tunneling interval was generally associated with deeper-seated structure. Tunnel route is within plane of seismic profiles (left, centre) and oblique to plane of profile (right). Images with permission of Sirius Minerals.

Interpretation of the seismic data coupled with legacy seismic data were used to build a revised predictive ground model (Figure 7) that was significantly more representative than the original model (cf. Figure 4).

In addition, a linear risk map (Figure 8) was built from the interpreted data to highlight those zones where disturbed host strata were likely to present more challenging conditions for tunnel and/or shaft excavation.

Zones disturbed by significant faulting were subsequently cored and investigated with wireline logging to confirm faulting and provide further detail on subsurface conditions including geotechnical properties to aid TBM design and significant benefits to planning of the construction programme including:

1. Verification of the decision made by Sirius Minerals prior to the 2017/2018 seismic campaign to re-align the MTS to avoid specific fault systems.

2. Significant reduction in project cost/time associated with attempting to drill suspected fault zones based on surface mapping alone.

3. Development of the ground model derived from the seismic data was tested with 3 no. cored boreholes with excellent correlation results increasing the confidence in areas which had not, or could not, be intrusively tested over the 37 km tunnel route.

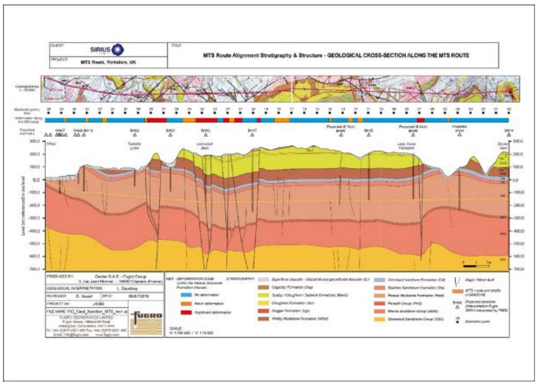
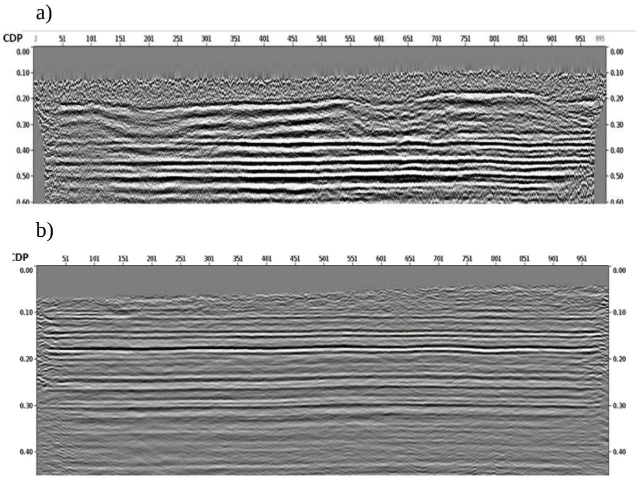


Figure 7: Revised ground model and linear risk map derived from BGS mapping, existing exploration seismic data from a public database and from interpreted data from the 2017/2018 Fugro seismic campaign.

Figure 8: Linear risk map of deformed strata based on 2017/2018 Fugro seismic campaign. Zoning of the tunnel route focussed risk mitigation decisions on those parts of the route with significant deformation within the tunneling interval.

4. Pre-Construction Geophysical Screening: Future Developments

Low-impact wireless seismic reflection profiling is one screening technique for developing a model to help understand ground risk below a largely rural environment. Multicomponent broadband seismic techniques are now being deployed to investigate the near surface for engineering applications. In particular, adoption of multicomponent (3C) MEMS-type receiver sensors for near-surface investigation is yielding significant benefits in terms of operational efficiency, quality and quantity of geophysical deliverables (Figure 9).



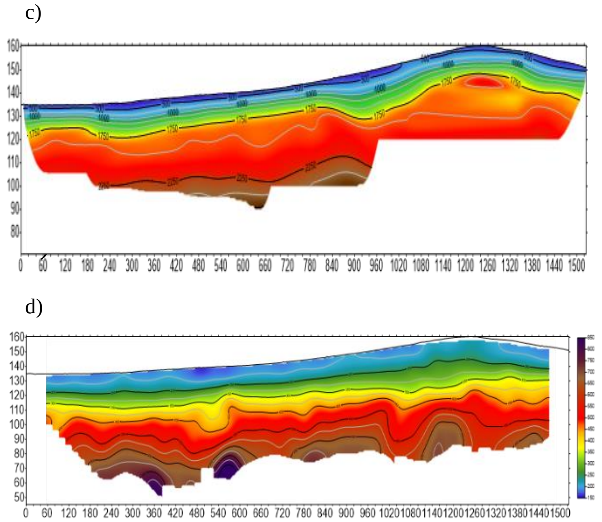


Figure 9: Multicomponent broadband acquisition of the complete seismic wavefield acquired at a sensitive nuclear site allows simultaneous capture of (a) S-wave reflectivity (b) P-wave reflectivity (c) P-wave velocity distribution through WET refraction analysis and (d) S-wave velocity distribution through surface wave analysis with time savings of about 25% over individual investigations. Images with permission.

Single multicomponent MEMS sensors provide the opportunity to capture, simultaneously, low-frequency surface waves and high-frequency body waves without some of the limitations of traditional geophone receivers (non-linear low frequency response, spurious high frequency response). Such an approach provides possibilities for more comprehensive early-phase screening of stratigraphy, structure and geotechnical properties for infrastructure development.

The inexorable growth of cities and an increasing need to develop the urban subsurface presents a significant challenge for developers wishing to manage their subsurface construction risks. The proximity of existing infrastructure and challenging surface and subsurface access creates a difficult environment from which to gather information of any sort, direct or remote. Some existing geophysical techniques can be readily adapted to a busy urban environment (such as microgravity to detect, for example, cavities and voids) but others such as most active-source seismic techniques have limited effectiveness largely due to the presence of environmental air and ground noise, complex near surface and lack of access.

However, the ambient acoustic noise field ever-present in the urban environment considered a problem in one sense could provide a means to help build the subsurface ground models of the future. H/V microzonation is a passive seismic technique that determines the characteristics of the horizontal and vertical components of the ambient wave field (surface wave component) and is well suited to situations of broadly softer over hard strata. Significant advances in passive seismic recording technologies and interferometric techniques developed for exploration and seismological applications (see for example [13,14]) might soon provide a means to better image both the structure (layering, discontinuities) and assess the geotechnical properties (e.g. small-strain shear stiffness) of the subsurface. Passive seismic tomography, involving the simultaneous deployment of potentially thousands of passive receivers, coupled with interferometric data processing could play a vital role in building ground models to provide subsurface insight for future urban developments.

Conclusion

Analogous with advances in medical diagnosis using scanning techniques, preconstruction geophysical screening creates more opportunity to avoid unwanted outcomes such as design inefficiency, wasted cost, and extended construction schedules. Based on evolving low-impact seismic sources, wireless receivers and broadband multicomponent acquisition techniques, technical developments initiated in the exploration sector will continue to be migrated to the engineering sector to improve the understanding and management of ground risk for infrastructure development and at the same time meet the needs of key project stakeholders.

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