Cite this article

Eddies R, Wood R, Haynes A, Warburton D and Pressdee C (2020)
Screening ground risk in underground works as part of a predictive modelling approach.
Proceedings of the Institution of Civil Engineers – Civil Engineering **173**(5): 49–57,
<https://doi.org/10.1680/jcien.19.00035>

Research Article

Paper 1900035

Received 17/07/2019
Accepted 22/10/2019 Published
online 02/01/2020

Keywords: infrastructure planning; risk
& probability analysis; site investigation

Published with permission by the ICE under the
CC-BY 4.0 license.
(<http://creativecommons.org/licenses/by/4.0/>)

Civil Engineering

ice Publishing

Screening ground risk in underground works as part of a predictive modelling approach

Rod Eddies BSc, MSc, PhD

Global Director Land Geophysics, Fugro, Wallingford, UK

Ray Wood MA(Eng), MBA

Global Director Land Site Investigation, Fugro, Wallingford, UK

Asher Haynes BSc

Project Engineer, Sirius Minerals Plc, Scarborough, UK

David Warburton BSc, MSc

Project Geologist, Sirius Minerals Plc, Scarborough, UK

Chris Pressdee BSc, MSc

Tunnel Lead (Europe), Fugro, Wallingford, UK

Tunnels and underground spaces are expensive to build, and the ground continues to present a key source of construction risk. This paper outlines the tangible benefits of an iterative and predictive ground-modelling approach to manage subsurface risk for key subsurface project stakeholders, namely owners, designers and constructors. Using a recent case study from the UK mining sector, it highlights how a well-designed and well-executed pre-construction geophysical screening process can play a vital, early role in reducing uncertainty in the ground, thereby improving the management of underground construction risk.

1. Introduction

Increasingly crowded urban centres and growing environmental factors are driving more infrastructure underground. The number of significant tunnelling and underground space projects is expected to remain high into the future across the globe. Much of a subsurface construction project's delivery risk can lie in the ground, so accurate and reliable site characterisation – including early geophysical screening – can hold the key to managing this risk effectively.

Tunnels and underground spaces are expensive infrastructure assets to develop and build, with actual tunnelling costs in Europe (Figure 1) of between €10 million and €50 million per kilometre (HM Treasury, 2010) and total project costs of on average about €200 million per kilometre. This could rise to four or five times this amount for tunnelling in the most challenging ground conditions and congested urban areas, such as in the case of the planned twin-bore Silvertown Tunnel in London (TfL, 2019).

Well-designed and well-constructed tunnels can provide long service (e.g. underground infrastructure built in the Victorian era in London), but remediation of poor performance is expensive and highly disruptive to heavily used infrastructure assets (e.g. Glendoe Hydro Tunnel collapse in 2009 (Hencher, 2019),

in which the project owner claimed about €145 million of compensation on a scheme costing €155 million). Transport for London (Nicholas, 2018) has indicated construction costs of about €0.23 million per linear metre and a lifetime budget of €1.4 billion per kilometre for road tunnels with a design life of 120 years.

Linear underground assets experience challenges, issues and failures locally due predominantly to changes in subsurface conditions over a relatively short extent. Managing the whole-life risks associated with route selection, design, construction and use needs a full understanding of the subsurface conditions and their interaction with the underground structure. Effective management of ground risk requires that site characterisation efforts are scoped and planned to maximise the foreseeability of subsurface conditions along the entire construction alignment as they relate to

- design of cost-efficient construction
- constructability and selection of excavation equipment and methods
- pricing – particularly with respect to the assumption of ground risk by the constructor
- effect on nearby structures and facilities
- long-term performance.

During the past decade there have been quantum advances in remote sensing geophysical techniques and in situ test methods directly relevant to identifying, assessing and ultimately managing ground risk in underground construction. Yet the industry generally fails to avail itself of these advances, favouring traditional approaches known to contribute to disputes and cost and time overruns. This is partly due to a lack of familiarity with such advances by the tunnelling industry but partly due to a culture of seeing past practice as a ceiling rather than a floor to future progress.

The gearing between the costs of site characterisation and final construction cost is such that the return on incremental investment of performing the right site characterisation well is huge, often 50 times or more. The industry knows well the cost of poorly executed geotechnical exploration through the costs and delays caused by claims for differing site conditions or unforeseen ground conditions, but little analysis is undertaken on the cost of avoidable over-engineering or excessive ground risk management premiums in bid prices for projects that are completed with few ground-related issues.

Figure 1. Effects of tunnel outer diameter on unit costs

2. Tunnelling cost overruns and how to avoid them

A number of studies have been conducted during the past few decades (including Clayton (2001), National Research Council (1984), Flyvbjerg *et al.* (2004), Flyvbjerg (2014) and Boeckmann and Loehr (2016)) studying the effect of ground conditions (among other factors) on final cost overruns of capital works infrastructure projects and the relationship between project cost overrun and the amount spent on site characterisation.

Whereas many of the data underpinning the studies go back to projects from the 1970s, 1980s and 1990s, and really need further studies to update them, the studies provide evidence that the situation has not greatly improved in the intervening period to the present. These studies and others all indicate the same general conclusions (Table 1) on the themes of overrun, capital costs and ground risks.

Table 1. Cost overrun studies – study themes and key conclusions

Study themes	Key conclusions
Overrun	Tunnel projects tend to overrun by between 10% and 30%, when final outturn cost is compared to initial bid price, with larger projects tending to have larger percentage overrun
Capital cost	Typically, less than 1% of the capital cost is spent on site characterisation, but when the investment in site characterisation is increased, cost overruns are usually significantly reduced
Ground risk	The main sources of ground risk are the proper definition of the boundaries and properties of soil and rock and groundwater conditions

Table 2. Key ground/structural challenges of the tunnel life-cycle

Tunnel developmental phase	Key challenges (ground and structure)
Pre-construction (this paper)	The risk of overly conservative design and overly long planning and design schedules due to uncertainty in ground conditions, late availability of site investigation data, and uncertainty related to time-dependent geological and hydrogeological behaviour
Construction	The risk of construction delays due to unforeseen ground conditions, avoiding and/or preventing geotechnical failure. Problems arising from unforeseen ground conditions that could be foreseen with the right site investigation and integration of these data into a dynamic ground model
Operational	The risk of operational failure or costly remedial schemes due to unforeseen but potentially foreseeable changes in structural conditions and/or ground conditions

2.1 Effective management of ground risk

Effective management of ground risk is critical for the successful delivery of underground projects. Konstantis *et al.* (2016) reported that out of the four main sources of tunnel hazard, ground conditions were key in three, namely geological and groundwater, construction techniques and design. Table 2 summarises the key geotechnical challenges that underground project developers and owners face during the main life-cycle phases.

Whereas cost overrun has many sources, failures during construction are disruptive leading to significant increased costs, delays to completion and often threaten life safety. Following publication of the *Joint Code of Practice for Risk Management of Tunnel Works* (British Tunnelling Society, 2003), Ronan Gallagher, head of the civil engineering underwriting team at Allianz Global Risks in Munich, declared that ‘tunnel construction is one of the riskiest insurance fields’ and ‘When an accident occurs, it often reaches catastrophic proportions’. If a tunnel-boring machine becomes stuck in unforeseen ground conditions, the cost and disruption of the rescue shaft needed to remedy the situation is usually considerable. Some US\$100 million to US\$140 million was required to rescue the Big Bertha tunnel-boring machine for repairs to its cutter head on Seattle’s SR99 Alaskan Way Viaduct replacement tunnel (Lindblom, 2016).

Comprehensive geodata from the five ‘G’s – geospatial, geological, geophysical, geotechnical and geohazard – are required to develop a high-fidelity representation of the ground conditions surrounding a tunnel alignment and its access and ventilation shafts. 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, which leads either to over-engineering and economic waste, or to 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. This all results in reduced return on investment from that expected. Civil engineering geodata serve three primary purposes centred on design, pricing and quality (Table 3).

Table 3. The primary purposes of geodata for tunnelling projects

Purpose of geodata	Description
Tunnel design	Geodata inform engineering design – the objective being to develop safe and economic construction
Construction pricing	Geodata inform the pricing of the construction by the contractor, important for the selection of suitable tunnelling machinery and the avoidance of exorbitant pricing of the management of ground risk
Quality	Geodata confirm that engineering objectives have been met in construction – this is particularly important for urban tunnelling projects where tunnel construction can have a considerable effect on adjacent facilities

2.2 Integrated site characterisation and progressive updating of ground model

It is an old and oft-repeated adage of the civil engineering industry that every project pays for good site characterisation, whether or not it is performed. The economics of civil engineering projects mean (as borne out by the studies referenced earlier) that if adequate site characterisation is not performed, cost overruns will often be an order of magnitude more than the money apparently saved on initial site characterisation (Mott McDonald and Soil Mechanics Ltd, 1994). It is self-evident from geological considerations that linear projects such as tunnels will experience issues, challenges and ultimately problems locally and likely over a relatively limited extent of the alignment.

A more effective approach (as summarised in Table 4) is to characterise the overall geological context and sequence along the alignment using remote sensing geophysical techniques that essentially ‘slice’ the ground to allow more effective targeting of the relatively expensive intrusive investigations, as described in Eddies and Wood (2014). In this way the intrusive investigation can be targeted to characterise the full depth, breadth and range of site conditions and enhance the value of the geophysical information. Remote sensing will allow more time and resources to focus on the techniques that should be included within the intrusive investigations to best serve the joint needs of designer and constructor. More intrusive investigation should be concentrated in areas of complex geology and challenge, while wider spacings

can be adopted when geological conditions are shown to be more uniform. A well-integrated remote sensing and intrusive exploration provides all the information necessary to constrain interpolation of site conditions along the entire alignment.

Geotechnical exploration is performed to define site conditions. At the start of any programme, uncertainty in this regard is at its highest. As the phases of the site characterisation unfold, the designer becomes progressively better informed about the site. For maximum utility and value for money of the geodata, the site characterisation programme must be structured such that the project designer responsible for scoping the site characterisation programme receives field data, converted to useful information in virtual real time. This allows on-the-fly adjustment of the remaining scope of the programme, informed by information gathered to date.

Web-based platforms that report site information at the earliest opportunity ensure that relevant insights are secure, timely and readily accessible to key stakeholders, meaning decisions are made in time to make a difference rather than waiting for a final report, avoiding disappointment that information could have been more valuable if timely modifications to the scope of the investigation had been made.

A continuously updated ground model approach as proposed by Parry *et al.* (2014) is a means to achieving uncertainty reduction and preventive ground risk management through iterative data addition (from integrated site characterisation activities), guided by geological expertise and knowledge. Advances in tunnel-boring machine technology mean that it is possible for a single machine design to

Table 4. Summary of pre-construction phase dynamic ground model approach for tunnels (note: urban environments might place significant constraints on this approach)

Phase	Stage	Description	Key tasks	
Pre-construction	1	Historical data review/desk study	<ul style="list-style-type: none"> Define sources of subsurface uncertainty Review of historical data Initial conceptual ground model development and zonation of route for geohazard potential and geotechnical variability 	Ground model and data management solution including monitoring and online information management (single point of truth, web-based)
	2	Reconnaissance field study	<ul style="list-style-type: none"> Reconnaissance field studies – for example, to map geomorphology and hydrogeological behaviour (monitoring) Update initial ground model with geomorphological interpretations 	
	3	Initial geotechnical and geohazard zonation	<ul style="list-style-type: none"> Undertake initial phase of trial pits, boreholes, cone penetration testing, in situ and lab tests Zonation of the site based on mapped/proved and potential geohazards/ground risks/geotechnical properties Undertake uncertainty and gap analysis Scope and design geophysical studies, including pilot stages to assess efficacy of approach 	
	4	Geophysical screening	<ul style="list-style-type: none"> Carry out geophysical field studies Integrate and calibrate geophysical responses Update ground model and refine zonation with geophysical interpretation Scope and design further intrusive studies, drilling, cone penetration testing, samples, borehole geophysics Undertake uncertainty and gap analysis for any necessary proving of ground 	
	5	Targeted intrusive investigation	<ul style="list-style-type: none"> Carry out trial pits, cone penetration testing, intrusive drilling, sampling, in situ and laboratory testing, monitoring Integrate and reconcile intrusive data 	
	6	Detailed ground modelling	<ul style="list-style-type: none"> Update model with intrusive data Define final model uncertainty and potential sources of error Format and transfer final model for end use, such as digital transfer to project design teams for mitigation measures

Figure 2. Final integrated ground model provides a three-dimensional representation of geotechnical and hydrogeological properties, stratigraphy and geohazards for tunnelling developments (courtesy of Chris Coleman, Fugro)

operate effectively in a variety of mixed face tunnelling conditions. However, unforeseen but potentially foreseeable conditions for tunnelling could include problematic ground associated with

- weak strata (e.g. gypsiferous deposits)
- disturbed strata (e.g. faulting)
- obstructions (e.g. flints in chalk)
- hydrogeological conditions (e.g. zones of high permeability)
- lateral facies changes
- squeezing ground
- rock burst
- swelling
- mixed face conditions.

Unforeseen problems are not restricted to excavating the principal tunnel structures. Temporary works, side tunnels, ventilation shafts and portals also present risks if the ground conditions are not fully understood. A continuously updated ground model, supported by an online data management solution, can evolve from a conceptual phase through to a full representation of subsurface conditions. This will provide a developer with a means to visualise subsurface challenges at the earliest stage possible and then manage the foreseen risk in a timely manner (Figure 2).

For most projects, early investment in a thorough site characterisation will be rewarded with real economic value for the project. This will be measured in reduced design time, improved safety, shortened schedule and less downtime and standby. A high-fidelity predictive ground model approach, properly and economically developed through a phased and integrated investigation strategy, has benefits for all tunnel project stakeholders (see Table 5).

2.3 Apportionment of ground risk between contract parties

In underground excavations it could be argued that the key uncertainties are mainly epistemic and depend on the level of information available. This is an important definition as, in principle, there will be no unforeseen variations due to randomness of subsurface properties if the subsurface can be fully represented in some way.

Table 5. Summary of key benefits of a predictive ground model screening approach for key tunnelling project stakeholders

Stakeholder	Benefits
Owner	Potentially reduces the site investigation scope in some areas of the site by way of continuous evaluation and integration of data allowing regular gap analysis and decision-making Reduces the length and costs of the design phase Avoids unnecessary cost by targeting intrusive activities in a spatially optimised way More cost-effective design, reducing over-engineering and capital cost The ability to transfer ground risk fairly to the party best able to manage it (the constructor) without an exorbitant risk price premium being included in bid prices Reduction and possible elimination of differing site conditions claims, leading to the avoidance of many sources of cost and schedule overrun
Designer	Better visualisation of ground variability and to assess the heterogeneity of ground parameters Better characterisation of the ground allows progressive design with confidence and the carefully managed elimination of over-engineering, likely to represent project capital cost savings many times the marginal cost of the improved site characterisation studies Professional risk exposure is better managed
Contractor	Acceptance of ground risk at an economically acceptable bid price More conducive to a true partnering relationship leading to more certain project delivery without the adversarial need to prosecute claims for contractor survival or profit

The tunnelling industry pioneered the use of geotechnical baseline reports (e.g. see Essex (2007) as an objective mechanism for the apportionment of ground risk between project owner and constructor. Such reports are developed from the exploration data and design considerations but focus on the constructability issues that affect project bid prices. They allow the effects of ground

conditions that differ from the baseline to be treated and valued as varied work, entitling the constructor to time and contract profit, and reducing the likelihood of adversarial claims.

A well-scoped and well-integrated site characterisation programme including geophysical screening allows the development of a robust geotechnical baseline report less open to interpretation and equitable to all parties with the associated reduction or even elimination of differing site condition claims.

3. Pre-construction geophysical screening for tunnels

To populate the initial ground model space along a tunnel route and to overcome uncertainties in the description of physical properties sometimes determined from a few direct sample points only, complementary geophysical screening through

early engagement with specialist practitioners and experienced consultants is increasing (Boeckmann and Loehr, 2016).

Several geophysical screening technologies deployed from the surface are highly suited to investigating tunnel developments. They are operationally efficient when deployed in linear surface profiling mode (see, for example, Reynolds 2014) and can be extended from two dimensions (depth, major tunnel axis) to three (depth, major and minor tunnel axes) where objectives dictate.

The following case study is an example of how geophysical screening significantly contributed to the initial predictive ground model and provided valuable insight into subsurface conditions for the owner, designer and constructor participating in a major UK tunnelling project.

3.1 Case study of pre-construction geophysical screening

Sirius Minerals proposed polyhalite fertiliser mine in North Yorkshire, UK, involves building a 37 km long, 250 m deep mineral transport tunnel (Figure 3). Low impact vehicle-mounted seismic sources and wireless receivers were key factors in building a predictive ground model for the tunnel, which is partly routed below the sensitive environment of the North York Moors National Park.

The Redcar Mudstone Formation described in Hesselbo and Jenkyns (1995), Powell (2010), and Hobbs *et al.* (2012) within the Cleveland basin is roughly 250 m thick and provides a continuous stratigraphic unit within which the proposed tunnel can be constructed. It 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 north-northwest–south-southeast and west-northwest–east-southeast trend.

The objectives of the investigation were to highlight the upper and lower contact of the Redcar Mudstone Formation and to determine the possible presence of faults and fault zones within the tunnelling interval that could negatively impact tunnel 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.

An initial conceptual model (Figure 4), based on British Geological Survey surface mapping and existing deep exploration

Figure 3. Schematic design for the proposed 37 km long mineral transportation system for a polyhalite fertiliser mine in North Yorkshire (courtesy of Sirius Minerals)

Figure 4. Initial ground model for the tunnel route was largely based on British Geological Survey information – note the presence of largely vertical faults throughout (courtesy of Arup and Sirius Minerals)

Figure 5. Tunnel route alignment, surface geology and seismic survey lines

seismic data, highlighted the presence of faulting but with only conjectural information relating to the tunnelling 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. Approximately 90 km of seismic data (Figure 5) were acquired in 2017 and 2018 by Fugro as part of the tunnel route screening process, along discrete profiles generally following roads, tracks and fields.

A low impact, highly manoeuvrable ‘vibroiseis’ seismic source, similar to a medium-sized agricultural tractor (Figure 6), eliminated the need for explosives 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, enabling a continuous overlap with existing exploration and publicly available seismic data. It obtained deep structural geological information and gave a better understanding of the likely conditions at the tunnelling interval.

Wireless seismic receivers were deployed along the route every 5 m (Figure 6) and ‘shots’ were acquired between each receiver to yield a maximum fold of 100 (100 × oversampling of each subsurface reflection zone). The combined use of these technologies yielded a very small footprint approach with small field crew sizes (six field staff) and minimal impact on the environment and surrounding communities. It also 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 tunnelling interval. Considering the interpreted fault distribution, deformation zones were identified where the geometry of reflectors was disturbed due to faulting and fracturing. These zones were characterised by dip variations and breaks in the reflectors (Figure 7(a)). Zones where the reflectors appeared to be well defined but with clear dip variations were also considered as likely deformation zones, despite the absence of obvious discontinuities (Figure 7(b)).

Figure 6. Wireless seismic receivers on the surface capture the subsurface reflected signals from a truck-mounted vibroseis seismic source

Figure 7. Examples of seismic profiles showing (a) fault zone (deformation zone) based on dip variations and reflector discontinuities, and (b) dip variations but with no evidence of reflector breaks or discontinuities (courtesy of Sirius Minerals)

The base of the Redcar Mudstone Formation 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 tunnel horizon, evidence of minor deformation and evidence of significant deformation (Figure 8). Interpretation of the seismic data coupled with legacy seismic data was then used to build a revised predictive ground model (Figure 9). This was significantly more representative than the original model (compare with Figure 4). In addition, a linear risk map (Figure 10) was built from the interpreted data to highlight those zones where disturbed host strata were likely to present

Figure 8. Examples of seismic profiles from pre-construction geophysical screening within tunnel plane (left and centre) and oblique to tunnel plane (right) showing varying evidence of deformation (courtesy of Sirius Minerals)

Figure 9. Revised ground model and linear risk map derived from British Geological Survey mapping, existing exploration seismic data from a public database and from interpreted data from the 2017/2018 Fugro seismic investigation

Figure 10. Linear risk map of deformed tunnelling strata based on the 2017/2018 Fugro seismic investigation – zoning of the tunnel route focused risk mitigation decisions on those parts of the route with significant deformation

more challenging conditions for tunnel and shaft excavation. The linear risk map was zoned as shown in Table 6.

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 tunnel-boring machine design. This provided significant benefits to planning of the construction programme, including the following.

- Verification of the decision made by Sirius Minerals prior to the 2017/2018 seismic investigation to re-align the transport tunnel to avoid specific fault systems.
- Significant reduction in project cost and time was associated with attempting to drill suspected fault zones based on surface mapping alone.
- Development of the ground model derived from the seismic data was tested with three cored boreholes, with excellent correlation results. This increased confidence in areas which had not, or could not, be intrusively tested over the 37km tunnel route.

4. Future developments of pre-construction geophysical screening

The authors have demonstrated the benefit of deploying wireless seismic reflection profiling as one screening technique for developing a model to help understand ground risk in a largely rural environment. However, 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 create 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. 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, which is considered a problem in one sense, could provide a means to help build the subsurface ground models of the future. Horizontal and vertical micro-zonation 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 (e.g. Tertiary and younger sediments over the Cretaceous Chalk below London). The method (e.g. see Nakamura (1989)) uses a single triaxial seismic receiver to yield a depth to an underlying stiffer and faster layer, with an assumed or known velocity structure.

Significant advances in passive seismic recording technologies and complex processing techniques (such as seismic interferometry) have been developed for exploration and seismological applications (e.g. see Wapenaar *et al.* (2019)). These might soon provide a better means to image the structure (layering, discontinuities) and assess the geotechnical properties (e.g. small strain shear stiffness) of the subsurface for underground construction projects. 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 help de-risk future subsurface urban developments.

Table 6. Linear risk map zonation criteria based on seismic interpretation of deformation and/or faulting

Interpreted extent of deformation	Interpretation criteria	Linear risk map colour
No deformation	Characterised by an absence of deformation or by deformation below seismic resolution (fracturing or faulting with <10m of vertical offset)	Blue
Minor deformation	Intense fracturing (exhibiting clear discontinuities within the reference seismic facies) or faulting with 10–15m of vertical offset. This type of deformation is typified by continuous perturbations of the seismic reflectors through a sufficiently continuous thickness of deposits to be considered as a fault. Vertical offset not always clearly expressed	Orange
Significant deformation	Characterised by faulting with >15m of vertical offset	Red

5. Conclusions

Tunnels and underground space form a part of the strategic national infrastructure and involve significant investment, warranting good site characterisation based on the evolution of a predictive ground model to manage those risks, significant for many projects, that lie in the ground.

Analogous with advances in medical diagnosis using scanning techniques, pre-construction geophysical screening can make the potentially unforeseen foreseeable. Through the evolution of the predictive ground model, this creates the opportunity to avoid unwanted outcomes such as design inefficiency, wasted cost and extended schedules.

Organisations involved in site characterisation activities are fully aware that the tunnelling sector sees advanced technical capability in site characterisation to be an attractive driver, provided cost efficiencies and improvements to the schedule can be made.

Correspondingly, and as highlighted by the case study in this paper, subsurface developers are increasingly aware that improved site characterisation will yield a high incremental return on the additional modest investment. The transition is from a conventional to a 'good' investigation, incorporating appropriate advanced and developing complementary technologies, including geophysical screening, alongside traditional approaches.

Founded on geoscientific knowledge, the predictive ground model approach, including geophysical screening as one of the critical early-stage activities, should help to drive residual ground risk in tunnel construction down to acceptable levels, with tangible benefits in cost, quality and schedule.

Acknowledgements

The authors thank Sirius Minerals for their kind permission to publish information relating to the North Yorkshire polyhalite project, geological consultants Cédric Duvail and Lucie Baudouy of Fugro for their interpretation work leading to the revised ground model and linear risk map for the project, and Fugro's UK consultancy team led by Chris Coleman for the ground model imagery and assistance with Table 4. The authors also thank two anonymous reviewers for their constructive comments.

References

- Boeckmann AZ and Loehr JE (2016) *Influence of Geotechnical Investigation and Subsurface Conditions on Claims, Change Orders, and Overruns*. Transportation Research Board, Washington, DC, USA.
- British Tunnelling Society (2003) *Joint Code of Practice for Risk Management of Tunnel Works*. British Tunnelling Society, London, UK.
- Clayton CRI (2001) Managing geotechnical risk: time for change. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **149**(1): 3–11, <https://doi.org/10.1680/geng.2001.149.1.3>.
- Eddies R and Wood R (2014) Making the earth transparent – using engineering geophysics to help manage uncertainty and reduce project cost. *Ground Engineering*, November, pp. 26–30.

- Essex R (ed.) (2007) *Geotechnical Baseline Reports for Construction: Suggested Guidelines*. Technical Committee on Geotechnical Reports of the Underground Technology Research Council, American Society of Civil Engineering, Reston, VA, USA.
- Flyvbjerg B (2014) What you should know about megaprojects and why: an overview. *Project Management Journal* **45**(2): 6–19.
- Flyvbjerg B, Skamris Holm MK and Buhl SL (2004) What causes cost overrun in transport infrastructure projects? *Transport Reviews* **24**(1): 3–18.
- Hencher SR (2019) The Glendoe Tunnel collapse in Scotland. *Rock Mechanics and Rock Engineering* **52**(10): 4033–4055.
- HM Treasury (2010) Annex G: Benchmarking: tunnels. In *Infrastructure Cost Review: Technical Report*. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/192589/cost_study_technicalnote211210.pdf (accessed 16/07/2019).
- Hessello SP and Jenkyns HC (1995) A comparison of the Hettangian to Bajocian successions of Dorset and Yorkshire. In *Field Geology of the British Jurassic* (Taylor PD (ed.)). Geological Society, London, UK, pp. 105–150.
- Hobbs PRN, Entwisle DC, Northmore KJ et al. (2012) *Engineering Geology of British Rocks and Soils: Lias Group, Land Use, Planning and Development Programme*. Internal Report OR/12/032. British Geological Survey, Nottingham, UK.
- Konstantis T, Konstantis S and Spyridis P (2016) Tunnel losses: causes, impact, trends and risk engineering management. In *Proceedings of the World Tunneling Congress, San Francisco, CA, USA*.
- Lindblom M (2016) Bertha's woes grind on: cost rises, tunnel delayed until 2019. *Seattle Times*, 21 July.
- Mott MacDonald and Soil Mechanics Ltd (1994) *Study of the Efficiency of Site Investigation Practice*. Project report 60, E063A/HG. TRL, Wokingham, UK.
- Nakamura Y (1989) A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Railway Technical Research Institute Quarterly Reports* **30**(1): 25–30.
- National Research Council (1984) *Geotechnical Site Investigations for Underground Projects*. The National Academies Press, Washington, DC, USA, vol. 1. See <https://doi.org/10.17226/919> (accessed 16/07/2019).
- Nicholas J (2018) *British Tunnelling Society Tunnel Design and Construction Course Presentation (Road Tunnel Operation)*. British Tunnelling Society, London, UK.
- Parry S, Baynes FJ, Culshaw MG et al. (2014) Engineering geological models – an introduction: International Association of Engineering Geology (IAEG) Commission 25. *Bulletin of Engineering Geology and the Environment* **73**(3): 689–706.
- Powell JH (2010) Jurassic sedimentation in the Cleveland Basin: a review. *Proceedings of the Yorkshire Geological Society* **58**(1): 21–72.
- Reynolds JMR (2014) *An Introduction to Applied and Environmental Geophysics*, 2nd edn. Wiley, London, UK.
- TfL (Transport for London) (2019) *Riverlinx Named as Preferred Bidder for Silvertown Tunnel*. See <https://tfl.gov.uk/info-for/media/press-releases/2019/may/riverlinx-consortium-preferred-bidder-for-silvertown-tunnel> (accessed 10/10/2019).
- Wapenaar K, Draganov D, Snieder R, Campman X and Verdel A (2019) Tutorial on seismic interferometry: part 1 – basic principles and applications. *Geophysics* **75**(5): 195–209.

How can you contribute?

If you would like to comment on this paper, please email up to 200 words to the editor at journals@ice.org.uk.

If you would like to write a paper of 2000 to 3500 words about your own experience in this or any related area of civil engineering, the editor will be happy to provide any help or advice you need.