GETTING A PICTURE

Fugro's **Rod Eddies, Simon Brightwell** and **Ray Wood** discuss how tunnelling risks related to the ground and built structure can be managed into better stakeholder outcomes - such as accelerated construction, extended asset life and optimised return on investment - through integrated and appropriately phased use of modern geoscientific technologies

Editor's note

The original presentation at the October BTS evening meeting was due to be given by Rod Eddies, but due to illness, Simon Brightwell deputised. This article is a more complete version of the talk for the benefit of readers. As a result, the Q&A has less relation to the text, but has still been included for interest.

As Tunnels and Tunnelling goes to press, the recording of the evening meeting is not available online, but readers should be able to find it on the Institution of Civil Engineers website in the fullness of time.

Authors

Rod Eddies is the global director of Fugro's land geophysics group with extensive experience in both onshore and offshore geophysics for oil and gas, mineral exploration and engineering geophysics.

Simon Brightwell has three decades of experience in the application of engineering geophysics to integrated ground investigation and asset integrity surveys.

Ray Wood is global director of Fugro geoconsulting and a senior specialist in geotechnical engineering with overview of group projects involving land and marine ground investigation.

TUNNELLING, WITH OUTTURN COSTS FREQUENTLY exceeding EUR 200M (USD 226M) per kilometre, represents significant private and public investment. At the same time, according to Jesel (2018), every major tunnel might be seen as a prototype.

Recent figures from Transport for London (TFL) reveal that their budget for road tunnels is approximately GBP 205,000 (USD 262,000) per metre to construct, consistent with European budgets of between GBP 150 and 250M (USD 195-325M) per kilometre. TfL has also confirmed that the whole lifecycle budget for their tunnels is around GBP 1.3bn (USD 1.76bn) per kilometre, taking into account periodic maintenance over 120 years.

Managing the lifecycle risks associated with such critical infrastructure relies on a robust understanding of the ground and condition of the tunnel: from pre-construction (feasibility, planning and design) to the construction phase with its attendant ground risks and into the extensive operational phase and focus on maintenance. Overarching this, soil-structure interaction has impacts on all stages of the lifecycle.

Despite living in an era of rapidly developing site characterisation technology and geoscientific expertise, some tunnel developers remain reluctant to invest in a timely investigation that draws on the most appropriate methods and deploys them in a suitably comprehensive manner – 'doing the right things' and 'the things right' (Stille, 2017).

The design stage in particular offers a good opportunity for avoidance of wasteful overengineering and lower project capital cost as, very often, the project scope is not finalised. Key decisions made at this stage, such as choosing the optimal alignment and construction type and materials, can result in significant cost variance during construction.

OVERRUN

A number of authors have identified the relationship between cost overrun due to unforeseen ground conditions and overly modest site characterisation budgets. Though ground conditions are clearly not the only cause of major overrun, the industry has suffered a number of high profile and frequently very large insurance and contractual claims.

In 2005 Ronan Gallagher (head of the civil engineering 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."

Major insurance incidents in the 1990s included those in Munich, Hull and Heathrow. Prior to the relatively recent adoption of a number of tunnelling codes of practice, the cost of claims had reached such dimensions that the insurance industry began asking itself whether tunnel projects would be insurable at all in the future.

Without a sufficiently representative picture of ground conditions (perhaps summarised as the '5 Gs': geological, geotechnical, geospatial, geophysical, geohazard) owners or developers can find themselves feeling their way in the dark, encountering unforeseen but possibly

Table 1: Key ground/structural challenges of the tunnel lifecycle

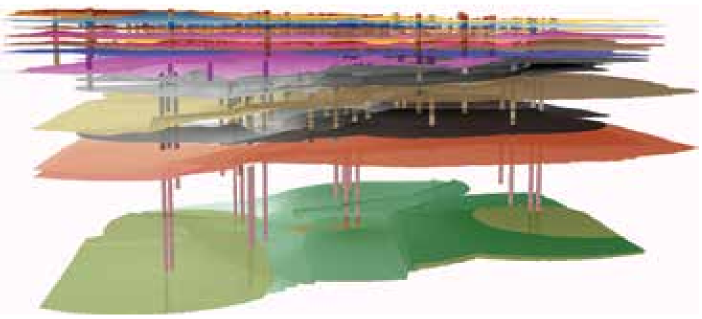
Developmental Phase	*Key Challenges (Ground and Structure)*
Pre-Construction	The risk of overly conservative design and overly long planning and design schedules due to uncertainty in ground conditions, late availability of site investigation data, and uncertainty related to time-dependent hydrogeological behaviour.
Construction	The risk of construction delays due to unforeseen* ground conditions, avoiding and/or preventing geotechnical failure, and implementation of continuous risk management.
Operational	The risk of operational failure or costly remedial schemes due to unforeseen but potentially foreseeable changes in structural conditions and/or ground conditions.

**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*

foreseeable ground conditions. It leaves the way open to inadequate or inappropriate design, construction issues, and a potential legacy of problems down the line including loss of public support and large insurance claims, all resulting in a different return on investment than that planned.

RECENT STUDIES

This is borne out by recent studies. Flyvbjerg et al (2003) presented results from the first major study of causes of cost escalation in transport infrastructure projects. They found that bridge and tunnel projects generally overran by about 32%, overrun being defined as: (outturn costs-initial cost estimate)/initial cost estimate x 100%. In addition, for bridges and tunnels, larger projects tend to have larger percentage cost escalations.



Above: *Figure 1, The Final Integrated Ground Model provides a representation of geotechnical and hydrogeological properties, stratigraphy and geohazards*

Worryingly, the study indicated that management of cost overrun for all projects including tunnels had shown little sign of improvement in 70 years. The policy implications of the study were clear: decision makers and planners should be highly concerned about delays (whatever the cause) and long implementation phases because they translate into risks of substantial cost escalations.

Generally ground risk is apportioned between owner and constructor using a Geotechnical Baseline Report with a proportion of the ground risk being retained by the owner. Reilly (2018) noted that both design-bid-build and design-build were used as contracting methods in the USA and, in a low-bid environment, would provide a potential mechanism for initial cost underestimation. The adversarial nature of the contracting relationship and the low bid environment is often a fertile environment for differing and unforeseen ground conditions claims.

Konstantis et al (2016) found that out of the four main sources of tunnel hazard, ground conditions were key in three, namely geology/groundwater, construction methodology and design. Table 1 summarises the key challenges that tunnel owners face during the main lifecycle phases.

PRE-CONSTRUCTION PHASE – THE ROLE OF THE DYNAMIC GROUND MODEL

One of the largest cost factors associated with tunnel construction is determining what geological conditions exist between the portals or shafts of a tunnel (Hoek, 1990).

Models and material properties of the ground will have a much higher degree of uncertainty than other building material like concrete and steel. The observational /modelling approach in tunnelling will be needed, therefore, in most cases, and can be regarded as part of the risk assessment and quality control (Stille, 2017).

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

Advances in TBM technology mean that it is possible for a single design to operate effectively in a variety of (mixed face) tunnelling conditions. However, unforeseen but potentially foreseeable conditions for tunnelling could include problematic ground associated with:

- karst (voiding, weak fill materials, strong lateral and vertical variability in geotechnical conditions, zones of high porosity/ permeability);
- faulting (juxtaposition of soils or rock with strongly contrasting geotechnical properties, zones of high porosity/ permeability/mechanical weakness)
- specific geological features (e.g. flints in chalk)
- hydrogeological conditions (e.g. flowing sands, artesian conditions)

Unforeseen problems are not restricted to excavating the principal tunnel structure(s); temporary works, side-tunnels, ventilation shafts and portals also present risks if the ground conditions are not fully understood. A dynamic ground model, supported by an online data management solution that through regular input evolves from a conceptual phase through to a full representation of subsurface conditions, provides a developer with a means to visualise subsurface problems at the earliest stage possible and then manage the foreseen risk in a timely manner (Figure 1).

A comprehensive dynamic ground model approach that could be applied to a pre-construction phase of a tunnel project would

Table 2: Summary of preconstruction phase dynamic ground model approach for tunnels (note: urban environments might place significant constraints on this approach)

Phase	Stage	Description	Key tasks	
Preconstruction	1	Historical data review/desk study	a. define sources of subsurface uncertainty b. review of historical data c. initial conceptual ground model development and zonation of route for geohazard potential and geotechnical variability	Dynamic ground model and data management solution including monitoring and online information management (single point of truth, web based)
	2	Reconnaissance field study	a. reconnaissance field studies, eg, to map geomorphology and hydrogeological behaviour (monitoring) b. update initial ground model with geomorphological interpretations	
	3	Initial geotechnical and geohazard zonation	a. zonation of the site based on mapped/proved and potential geohazards/ground risks/ geotechnical properties b. undertake uncertainty and gap analysis c. scope and design geophysical studies, including pilot stages to assess efficacy of approach	
	4	Geophysical screening	a. carry out geophysical field studies b. integrate and reconcile geophysical responses c. update ground model and refine zonation with geophysical interpretation d. scope and design intrusive studies, drilling, cone penetration testing (CPT), samples, borehole geophysics e. undertake uncertainty and gap analysis for any necessary proving of ground	
	5	Intrusive investigation	a. carry out intrusive drilling, sampling, in situ and laboratory testing b. integrate and reconcile intrusive data	
	6	Detailed ground modelling	a. update model with intrusive data b. define final model uncertainty and potential sources of error c. format and transfer final model for end use, eg, digital transfer to project design teams for mitigation measures	

comprise the stages in Table 2, characterised by baseline monitoring, online data management and cyclical revaluation of information resulting in iterative reduction of subsurface uncertainty (Coleman, 2018).

Web-based platforms ensure that relevant data are secure, up-to-date and readily accessible, facilitating real-time assessments and adjustments, with timely progress reporting and decision support, rather than waiting for a formal report to be completed.

For most projects, early investment in a thorough site characterisation will be rewarded with real economic value for the project that could be measured in reduced design time, improved safety, shortened schedule, and less downtime/standby.

In tunnel 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.

A representative dynamic ground model approach coupled with an online data management solution offers a number of benefits in terms of quality, cost effectiveness or scheduling improvement:

- Allows developers better visualisation of ground variability and to assess the heterogeneity of ground parameters;
- Reduces potential construction overruns by identifying all potential geohazards and geotechnical or other site constraints, thereby allowing effective management of subsurface challenges;
- reduces construction costs by reducing constructor price contingencies for ground risk, providing a sufficiently representative baseline geotechnical report that the construction contractor will be confident to reduce their risk premiums and advise on more constrained construction timetables;
- reduces the likelihood of needing additional mobilisations for supplementary site investigation; all potential constraints are identified sufficiently for design and mitigation and construction method selection in one pass;
- potentially reduces the site investigation scope in some areas of the site via 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.

A high fidelity ground model, properly and economically developed through a phased and integrated investigation strategy, has benefits for all project stakeholders as follows:

For the Tunnel Owner
- More cost-effective design, reducing overengineering and capital cost;
- The ability to fairly transfer ground risk to the party best able to manage it (the constructor) without an exorbitant price premium being included in bid prices; and
- Reduction and possible elimination of differing site conditions claims leading to the avoidance of many sources of cost and schedule overrun.

For the Tunnel Designer
- Better characterisation of the ground allows progressive design with confidence and the carefully managed elimination of overengineering likely to represent project capital cost savings many times the marginal cost of the improved site characterisation studies; and
- Professional risk exposure is better managed.

For the Tunnel Contractor
- Acceptance of ground risk at an economically acceptable bid price; and
- 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.

PRECONSTRUCTION PHASE: GEOPHYSICAL SCREENING FOR TUNNELS

To overcome uncertainties in the description of physical properties determined from a few direct sample points only, the importance of geophysical screening through early engagement with specialist practitioners and experienced consultants (Konstantis et al 2016) is increasing. This is because these methods can yield continuous soil/rock properties information along profiles or over the complete area under investigation.

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 (Eddies and Wood, 2014).

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 (Eddies and Wood 2014) and enabling better design decisions to be made.

Several geophysical screening technologies are highly suited to investigating relatively shallow tunnel developments as they are operationally efficient when deployed in surface profiling mode. They include most seismic, electrical, electromagnetic, gravity and magnetic methods, all of which can be extended from 2D (depth, major tunnel axis) to 3D (depth, major and minor tunnel axes) where objectives dictate and budgets allow.

As an example, in situ screening of small-strain geotechnical properties (shear wave velocity, shear modulus) along a tunnel route can be achieved through well-established surface wave profiling techniques to depths of about 30 metres. In fact, recent developments in interferometric surface wave methods can extend the depth of investigation for in situ ground stiffness characteristics to beyond 100 metres.

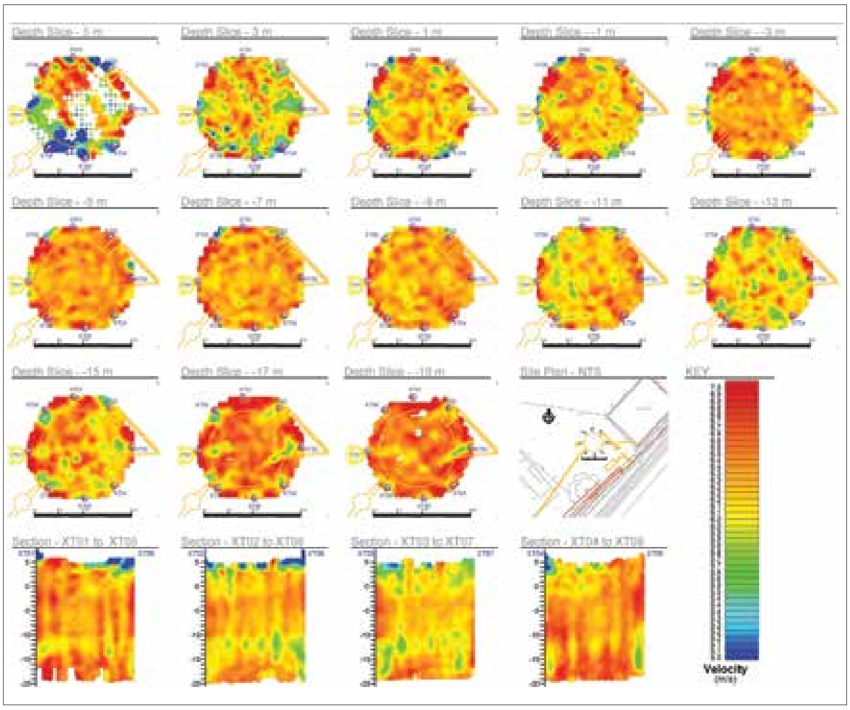
Surface geophysical methods allow a risk assessment well ahead of TBM operational planning to allow mitigation of risk in advance of construction activities at depths of less than about 50 metres.

For example, advances in broadband multicomponent seismic acquisition (3°C) mean that simultaneous acquisition is now possible of data from which a number of different analyses can be made for bedrock depth, soil stiffness and stratigraphy, and the presence of discontinuities such as faults or cavities pertinent to assessing pre-construction ground risk.

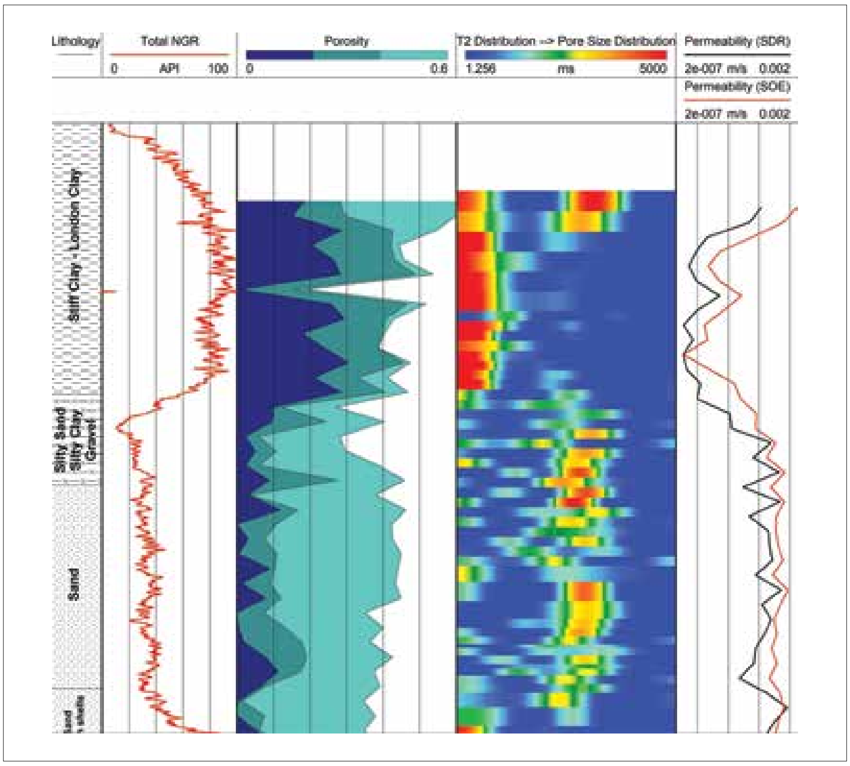
Other surface developments suitable for urban (and therefore noisy/difficult to access) tunnel environments include highly portable passive seismic methods (microzonation) that record low frequency ambient noise in horizontal and vertical directions and allow mapping of bedrock morphology or that of stiffer/deeper layers with highly portable equipment. A recent reconnaissance microzonation survey across London by Fugro effectively tracked the top of the Chalk below Tertiary and Quaternary deposits.

This type of study opens up possibilities for more detailed detection and mapping of deeper features in the bedrock that might extend into younger cover materials (e.g. faulting) through which future TBM operations are planned – such as planned HS2 Phase 1 tunnels driven through sediments overlying Chalk. Thus, with the right geological conditions, passive seismic methods can provide a means to build a reconnaissance risk profile for future buried infrastructure in busy urban environments.

Tunnels are frequently located below areas of multiple land ownership involving complex stakeholder relationships. In this scenario, wireless seismic technology 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 and HSE exposure of field operations. Such technology was a key factor in building a risk model for



Above: ***Figure 2, 3D seismic tomographic imaging at multiple depths can be applied to planned shaft structures to verify the absence of potentially hazardous conditions such as faulting or voiding***



Above: ***Figure 3, The downhole magnetic resonance (DMR) method can yield in situ measurements of porosity and permeability in addition to quantifying bound and mobile water without pumping tests***

the Sirius Minerals polyhalite development in the UK involving a 37-kilometre-long mineral transportation tunnel.

Deep (> 50 metres) tunnels are generally beyond the investigation depth or optimal resolution of surface-based geophysical methods other than seismic methods or those deployed from boreholes. On the theme of access, not all tunnels are conveniently located for surface investigation activities. However, several geophysical methods can be applied to investigate conditions in the shallow transition zone (STZ) between land and water bodies where intrusive investigation can be physically difficult or prohibitively costly.

Beyond the main tunnel excavation, TBM launch and recovery shafts and large ventilation structures represent significant early cost and temporary works risk for developers. Borehole seismic tomography (Figure 2) and wireline logging techniques developed from the exploration sector allow vertical and lateral characterisation of shaft volumes to be made in 3D from a small number of exploratory boreholes.

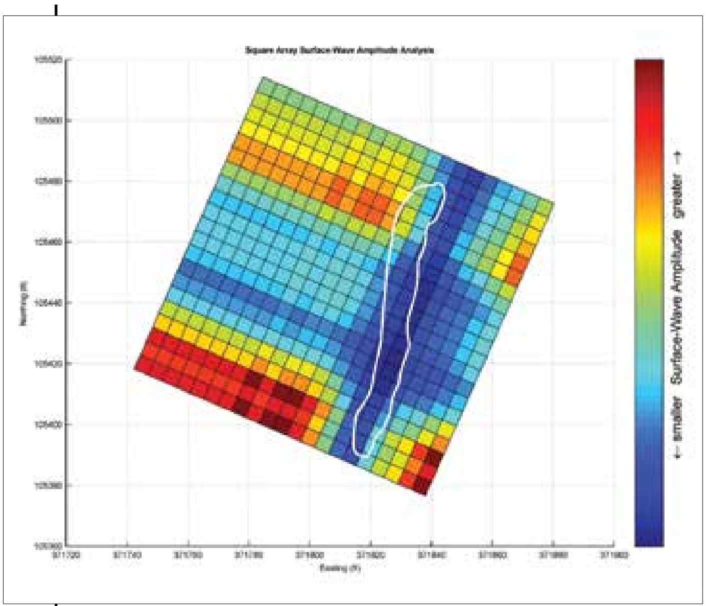
Significant value can be added to such investigations by incorporating measurement-while-drilling (MWD) data and analyses into the localised ground model. MWD data are relatively inexpensive to acquire and process yet, if properly executed, have the potential to yield vital detail at a vertical resolution better than many borehole-hosted tests, including wireline logging.

Hydrogeological conditions are another key consideration for tunnel designers and constructors.

Downhole magnetic resonance (DMR) technologies, recently migrated from the exploration sector in the form of slim-hole tools, can determine in situ porosity and permeability characteristics in saturated conditions (Figure 3). They can also quantify bound and mobile water fractions from boreholes with minimal calibration effort and without the need for lengthy pumping tests.

Areas of poorly recorded shallow mine workings or soluble strata present particular challenges for developers where hazardous features have no surface expression (eg HS2 tunnels planned through the UK Cretaceous Chalk) and detection, rather than characterisation, remains a key objective for the engineering geophysics community.

Recent developments in diffraction imaging and surface wave tomography (amplitude, velocity, resonance) using square field geometries offer some improvement. The technique, known as square array void mapping (SAVM), allows voids and cavities to be detected with



Above: ***Figure 4, Square array void mapping (SAVM) uses an array of seismic sources to investigate a 3D volume of ground and is ideally suited to tunnel investigations in non-urban environments. Voiding (indicated by the white line) can be diagnosed from zones of anomalous amplitude and/or low seismic velocity***

much greater confidence than traditional seismic methods (e.g. MASW, SASW, ReMI) which are optimised for determining shear wave velocity profiles rather than voids or cavities (Figure 4).

CONSTRUCTION PHASE – MONITORING, SCANNING AND RISK VISUALISATION FOR TUNNELS

Any tunnelling underground carries a risk of ground movements and potential negative impacts to nearby surface and subsurface infrastructure and property.

Recent geophysical developments aimed at managing ground risk during TBM operations include real-time seismic and radar-based look-ahead systems. But as with the limitations of surface methods, there is no universal panacea given the variability of ground from one tunnel to the next or along a specific tunnel route.

Some proprietary seismic systems (e.g. ISP and SSP, Herrenknecht) claim to provide some 'look-ahead' for voiding over 5 metres in diameter in hard rock conditions. These use surface wave analysis and can detect obstacles, like boulders or old sheet piles, through seismic reflection analysis in loose soil conditions.

Such systems are built into the TBM and can be used without interrupting face advancement. Other systems use the vibrations of the cutter head to generate acoustic signals that are captured in boreholes at more than 100 metres ahead of the tunnel face (e.g. Tunnel Seismic While Drilling, Brükl et al 2008). The data are then subject to processing similar to conventional borehole seismic methods to image for potential tunnelling hazards such as fault zones.

Probe drilling ahead of TBM operations allows radar tomography (mapping radar velocity variations) to be carried out which can be particularly effective in locating karst and cavities in dry rock. For the Steinbühl tunnel, Schmidt et al (2017) predicted a total of 284 air-filled structures using radar and gravity data; 191 were investigated with 170 structures confirmed, a hit rate of 89%.

Probe drilling also allows wireline logging of the rock mass to be carried out to characterise conditions ahead of TBM operations. Where excessive water pressures might be encountered, in hard rock fault zones, for example, wireline logging techniques can be applied horizontally in push-mode up to a few hundred metres with the protection of blow-out preventers/stuffing glands at the excavated face.

Long hole directional core drilling with wireline logging can be used to identify areas where there could be considerable variability across the tunnel face.

While it is recognised that a steered cored hole along the tunnel centreline is significantly preferable to a few vertical or subvertical holes intersecting the tunnel horizon, for large diameter tunnels, say >10 metres in diameter, there can be considerable variability in conditions across the face. Confirmation of such variability using in-hole geophysics could be very beneficial.

Advances in tunnelling, such as improved control of face pressure or improvements in shotcrete for the New Austrian Tunnelling Method (NATM) and enhanced ground treatment like compensation grouting, have led to greater control of volume loss, the principal parameter of ground movement.

Volume loss has been reduced – from upper values of between 2% and 3% in the 1990s down to generally less than 1% today for tunnels constructed in London - using modern tunnel boring machines (HS2, 2013). But it is in the interest of developers and other stakeholders to demonstrate compliance with design predictions or other reference thresholds through monitoring, and, indeed, to establish baseline data through monitoring during the pre-construction phase.

For Crossrail, more than 65,000 sensors were used to monitor the effect of tunnelling and dewatering on nearby buildings and structures. Data acquisition included surface measurements (robotic theodolites with targeted prisms on buildings and hand held theodolites) and subsurface measurements (piezometric measurements to detect small changes in water level and extensometers to measure movement below ground level).

Following construction, InSAR (interferometric synthetic aperture radar) satellite data sources can be used to determine ground settlement or heave at millimetric accuracy. Imperial College performed permanent scatterer interferometry to build a settlement map for the Crossrail route and stations, revealing that settlements were much lower than that predicted ahead of construction.

For tunnel developments, quick and informed decision-making is critical in preventing failure costs and disruption through the implementation of timely preventative measures. A real-time overview of information, for example, ground movement, water levels, soil-structure interaction, is a key advantage for decision-makers, facilitating timely risk communication and helping engineers to identify and mitigate geotechnical risks.

A priori risk assessments, real-time subsurface and surface sensor observations, and updated model results provide input for

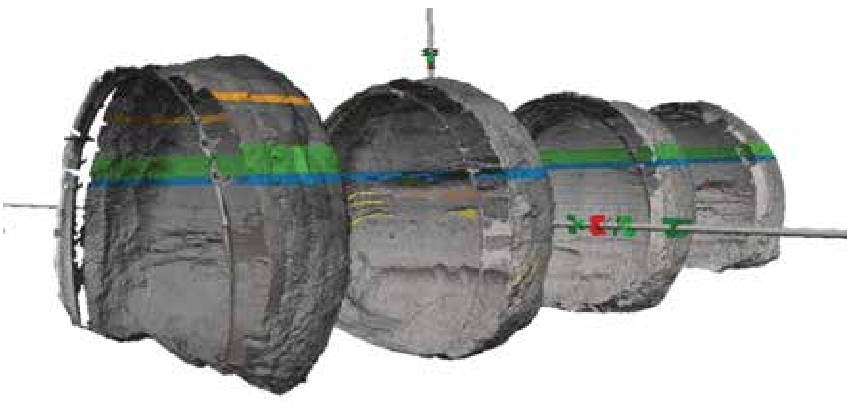
Table 3: Summary of construction phase methods of ground and risk assessment for tunnels

Phase	Description	Key tasks	
Construction	probe drilling from tunnel face	a. radar velocity tomography to detect voids and cavities (subject to conditions) b. seismic velocity tomography for detection of faults and other anomalous zones c. wireline logging in push-mode to determine geological, geotechnical and hydrogeological conditions (through blow-out preventers if necessary	*Dynamic ground model and data management solution (including monitoring and online information management (single point of truth, web based)*
	TBM-hosted look-ahead surveys	a. seismic reflection and surface wave investigation for faulting requiring boreholes ahead of the excavated face b. integration of key findings into ground model	
	laser scanning of excavated face	a. lidar surveys of exposed faces b. hyperspectral scanning of exposed faces c. build 3D models incorporating lidar and optical scanning data	
	borehole monitoring	a. groundwater monitoring b. ground movement monitoring c. pre- and post-compensation grouting monitoring	
	surface / subsurface/ structural monitoring	a. ground surface movement monitoring b. building movement monitoring c. monitoring within existing subsurface infrastructures	
	ground modelling	a. integration of key findings into revised construction-phase ground model b. communication and execution of mitigation measures as appropriate	

decision support following the key principles of the observational method (Peck, 1967). Heat maps driven by (sensor) data and analytics are applied to communicate project risks and opportunities with clarity.

Where tunnel excavation faces are exposed during construction, then a number of methods are available for assessment of conditions including laser scanning (lidar). By generating a point cloud at successive face excavations, a 3D representation of the tunnelled excavation volume and strata can be made.

Lidar can be combined with hyperspectral measurements (optical reflectance) to help build a geological model of the tunnel volume for monitoring of convergence, 3D geological and geotechnical analysis of excavated rock faces (Figure 5). Such an approach was key in the development of the tunnels developed for the ANDRA nuclear waste facility in NE France.



Above: ***Figure 5, Lidar imaging is an effective method for profile geometry and convergence analysis, excavation face mapping, and geological analysis combined with hyperspectral imaging***

Regular laser scanning of tunnels under construction allows overlays of successive tunnel profile scans on the theoretical tunnel design, so that overbreakage and underbreakage as well as movements can be detected and quantified.

Table 3 summarises key technologies for assessing and monitoring ground risk and quality assurance of tunnels during the construction phase.

OPERATIONAL PHASE – MONITORING AND MEASURING CHANGE

While the arguments for investment in a robust understanding of ground conditions to support design and construction are compelling, there is also a growing realisation that the flow of information must not stop there.

We design tunnels to last longer than other civil engineering assets; Thames Tideway, for example, has a 120-year design life. But we still rely on structures such as Network Rail's stock of Victorian rail tunnels or London's sewer network, which are already significantly older than that and expected to be in service for many decades to come.

Since replacement is prohibitive, they must be maintained. However, with utilisation typically close to capacity, the

Table 4: Contemporary approaches to condition assessment and structural monitoring for operational tunnels

Phase	Description	Key tasks	
Operational	visual and tactile survey	a. visual identification of surface defects b. basic acoustic sounding, eg, hammer tapping to detect areas of loose material	*Dynamic ground model and data management solution (incl. monitoring and online information management (single point of truth, web based)*
	laser and optical scanning	a. build 3D models incorporating lidar and optical scanning data b. measure and monitor change in physical dimension and shape (bulging, spalling, cracking) for structural assessment and gauging reasons	
	ground penetrating radar	a. continuous subsurface imaging to determine layer thickness and structure in non-metallic linings b. mapping subsurface elements such as reinforcement, steel ribs and hidden construction shafts c. assessment of condition: mapping delamination, voiding, moisture	
	ultrasonics and other acoustic methods	a. suite of acoustic methods to determine structure and condition b. detect voids and delamination, especially where steel density prevents use of radar c. measure strength and integrity of concrete d. thickness measurement, eg, of metallic lining	
	monitoring and instrumentation	a. a wide range of remote and contact-based measurement systems to record change in selected parameters over time b. structural movement in X,Y or Z axes, deformation, convergence c. development of defects such as cracks or excessive joint opening d. change in physical properties, eg, stress, strain e. environmental conditions, temperature, noise, humidity, water ingress f. ground settlement or distress to third party assets above tunnel	

opportunity to access, maintain or refurbish these tunnels is often extremely limited.

There are typically three crucial streams of information needed for safe and efficient maintenance:

1. An as-built record of the structure
2. A base record of its condition, for example, to target maintenance and refurbishment
3. An ongoing picture of change, based on monitoring both the structure and the surrounding environment, including third party assets

Table 4 highlights contemporary approaches to gathering these crucial data.

AS-BUILT STRUCTURE

Without an understanding of factors such as lining arrangement, joint detail, drainage or ground conditions, it is not possible to reliably assess the integrity of the structure or to interpret the structural implications of surface defects or movement.

The type of information typically required includes:

- Physical dimensions and shape;
- Lining type, thickness, strength and variability;
- Strengthening and supporting structures such as ground anchors or structural ribs;
- Geological and hydrogeological conditions

A continuous record of physical characteristics and shape, both of the main elements such as the lining and deck, but also of secondary features such as lighting, signing or power systems, is crucial for the purposes of gauging and clash detection.

In the case of older tunnels, the quality of records ranges from surprisingly thorough and accurate to non-existent. Where records are unavailable or unreliable, a programme of investigation is required, but the collection of a suitably comprehensive picture of surface and subsurface detail is often highly challenging.

Smarter data acquisition is therefore needed and technical development can be seen in many areas, particularly relating to laser-based technologies for measuring and recording physical structure. Point-cloud data sets acquired using mobile scanners can provide a comprehensive picture of internal dimension and attributes with a relative accuracy better than ±5mm.

For a subsurface perspective, non-destructive investigation methods such as ground penetrating radar, ultrasonics and impact echo can determine lining thickness and reinforcement detail. For a deeper view, a number of geophysical techniques more widely used in ground investigation have been adopted. Fugro geophysicists have, for example, successfully adapted electrical resistivity tomography (ground resistivity) for the detection of hidden construction shafts above railway tunnels, thus reducing the risk of deformation or collapse.

The collation and presentation of all the above information will typically involve building information modelling (BIM) applications, which ideally incorporate preconstruction information and provide a platform for data sharing and future updates.

However, the digital replica is only as good as the data collection, recording and storage, and while today's cloud-based data formats may be easily accessible in a decade, consideration must be given to how they may be read in a century.

CONDITION SURVEY

From the day of completion, a tunnel is exposed to forces that can alter properties relating to strength and integrity.

Those responsible for inspection and maintenance must therefore consider the specific characteristics of a tunnel and the risks it is exposed to in order to collect meaningful and useful information on which to base their decisions.

The type of information required includes:

- Material strength and integrity
- Movement/deformation
- Water movement and related formation of voids
- Corrosion or chemical deterioration

In the UK, Network Rail has traditionally relied on visual inspection and 'tactile surveys', that is, tapping the surface to detect areas of loose or 'drummy' brickwork, with more than 500 people required to assess 5.5 million square metres of brickwork in 338 kilometres of tunnels.

The move towards more sophisticated data acquisition is underway. By late 2017 there were five Digital Imaging for Condition Asset Monitoring (DIFCAM) systems in use on the UK rail network, collecting optical survey data to compare with previously captured data and identify potential new defects or deterioration such as cracks, spalling or bulging.

The number of people involved in site inspection has fallen significantly and Network Rail has quoted savings of GBP 5M (USD 6.51M) per year as a result of the change, which supports the drive towards a risk-based targeting of its GBP 35M annual refurbishment budget.

While the inspection of rail tunnels can be achieved on a relatively high frequency basis, many structures cannot be accessed without complex and expensive logistic arrangements.

The programme of inspection and testing of the Haweswater Aqueduct tunnels undertaken by United Utilities in 2016 is a case in point. Taking more than five years to plan and costing more than GBP 10M the inspection required temporary closure of the aqueduct that supplies most of Greater Manchester's drinking water.

Despite extensive contingency plans for alternative supply, the inspection and testing of 90 kilometres of siphons, pipes and concrete tunnels had to be completed in less than a month. Crucial to the data gathering initiative was development of bespoke multi-channel ground penetrating radar systems operated from battery-powered vehicles – an approach that gathered crucial intelligence on concrete condition and structure at a suitably high sampling density to provide the basis for future decision making (Figure 6).

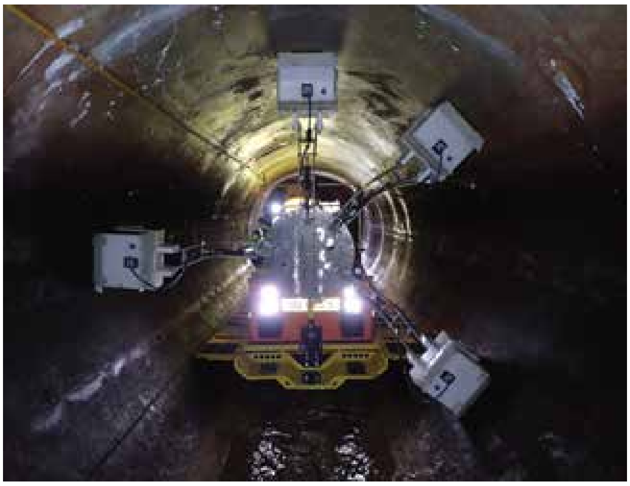
MONITORING CHANGE

While the importance of monitoring during the construction stage has been recognised for many years, its value to ongoing asset management is only just being fully realised.

The logistical challenges and costs of undertaking structural inspection and assessment using methods that require human access support the case for alternative technologies that enable remote data acquisition.

The oil and gas industry has long-relied on autonomous 'pigs' for machine-based inspection and integrity testing of pipelines, and there is considerable scope for increased use of automated and remote measurement in tunnels where human access is complicated.

The wider adoption of a 'smart infrastructure' approach based on remote measurement and permanent installation of instruments to monitor structural health parameters presents the sector with probably its biggest potential area for post-construction performance improvement.



Above: Figure 6, Fugro developed a bespoke multi-channel ground penetrating radar system to survey 40 kilometres of concrete tunnels at Haweswater Aqueduct in NW England. More than 800 profile kilometres of data were collected in less than two weeks

FINAL THOUGHTS

Good site characterisation, or making the potentially unforeseen foreseeable, 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 to be an attractive driver, provided that cost efficiencies and improvements to schedule can be made. In this article examples of advanced but available technologies that can add tangible project value through the tunnel lifecycle have been provided.

Correspondingly, tunnel developers are increasingly aware that improved site characterisation will yield a high incremental return on the additional modest investment going from a conventional to a 'good' investigation.

Founded on geoscientific knowledge, the dynamic ground model approach, including geophysical screening as one of the early-stage activities coupled with online data management and online decision support, should help drive residual construction risk down to acceptable levels with benefits in cost, quality and schedule.

Post-construction, the interaction between the built tunnel structure and the host ground continues to generate time-dependent risk through the extensive operational phase. Timely evaluation of structure and condition can also help manage these risks, yielding benefits measured in optimised maintenance effort and asset efficiency and longevity.

The continuum comprising the built tunnel structure and its host ground is rarely represented as a digital ensemble, even for the most recent tunnel projects, and yet it makes good sense not to separate the inextricably linked time-dependent structure and condition of both elements.

BIM as an optimisation tool can yield real but modest economic value to major projects, while lifecycle costs for tunnels can be very significant. Inevitably we are moving towards greater digitalisation and the digital twinning of everything for managing complete lifecycle risk.

Perhaps one of our bigger challenges now is how we reconcile the (near) certainties associated with BIM for built structures with the inherent and frequently time-dependent uncertainties associated with even the most detailed models of the ground – a real 4D digital challenge for all involved.

References

Jesel, 2018
Stille, 2017
Flyvbjerg et al, 2003
Reilly, 2018
Konstantis et al, 2016
Hoek, 1990
Coleman, 2018
Eddies and Wood, 2014
Herrenknecht ISP & SSP
Brükl et al 2008
Schmidt et al, 2017
HS2, 2013
Peck, 1967

Questions from the floor

Q: Andrew Smith, Joseph Gallagher (retired) – you highlighted groundwater but didn't cover it well. Can you get groundwater information from non-intrusive methods? In the end you have to drill a borehole.

A: There are effective ways of at least profiling distinct groundwater layers in the shallow subsurface, for example with ground resistivity electrical methods and in the deeper subsurface to some degree with seismic methods, but yes changes in groundwater tend to be less well defined and to have less impact, particularly on the seismic waveform than for example the transfer from ground to air or between different types of rock. So it's not easy to provide detailed information on that and we are dependant on boreholes.

Nuclear magnetic resonance (or "downhole" resonance is preferred term) requires borehole but provides precise, high-definition profiling on changes in groundwater level, flow, chemistry and a lot of information that is very useful for hydrogeology. That is broadly a geophysical tool, but it does need a borehole.

Q: Ivor Thomas, chair – Regarding York Potash and I notice your section in highly fractured ground. The big concern with Potash and tunnels is squeezing ground. Is your system able to characterise whether the ground in that fractured section will squeeze or not?

A: The key to that is you really want to make sure you do the right ground investigation rather than to do any investigation right. Issues of soft ground and squeezing ground I think you need to have an intrusive investigation of the soil to be confident you've characterised with relation to the geophysics the extent of that particular problem that has to be dealt with. In the interpolation of ground conditions between widely spaced, distinct sticks of information, drives contingency premiums and drives claims of unforeseen ground conditions. And I think what York Potash shows is with a certain capacity for GI, you see the geology is reasonably consistent over a length of tunnel, you can open out the borehole spacing. You can then take the boreholes you've saved and then tighten up the boreholes in the complex areas, and that's the real value of the non-intrusive. Particularly with a linear job like a tunnel, we're very interested in slicing the ground. The geophysics techniques slice the ground for you.

Q: Jonathan Turner, Radioactive Waste Management – One of the sources of uncertainty is fractures and I think fractures pose a particular challenge because they can be pervasive, they can and do occur on scales less than can be resolved by conventional seismic reflection. It may be beyond the scope of what you are talking about but I wonder if Fugro has made advances in terms of non-invasive methods of characterising pervasively fractured ground.

A: I think the response to that would be that the ability to use geophysics to resolve heavily or tightly fractured ground is going to be partly dependent on the depth of interest, it is a pattern throughout these techniques that you can achieve better resolution at shallow depths. So, it maybe be that at shallow depths it is possible. I would certainly expect to identify fractured zones, if not individual fractures. And the ability will decrease with depth.

Q: Sean Desmond, Tideway Central – I was wondering about the use of LiDar for mapping in tunnels, what turnaround do you get for undertaking a LiDar survey and how easily is it integrated into predictive ground models and can you use it for distinguishing different stratographic units?

A: Obviously the example there is in an excavated rather than a bored tunnel. It's of less use in a lined, TBM structure, but yes, it can be turned around quickly. It is certainly a matter of one or two days rather than weeks. Looking at the reflective response of the different mineral groups, it's a useful tool but depends on a geologist looking at the data. But the beauty is that it is non-contacting, non-destructive. You get your dataset and take it away, you are not delaying the work for long, it takes minutes to record the data. It is not a precise and absolute definition of different types of rock, but it is a good indicator of change.

Q: Steve Parker, Ferrovial – What do you see as new methods for UXO detection? I am talking about 0-20m depth in advance of 20t.

A: An interesting one that is keeping a lot of people busy. I just came back from Berlin. Things do move on, it is a challenging application in an urban, complex environment with a lot of ferrous metal because the preferred method is always going to be based on a magnetic sensor. You'll pick up every little metallic thing at the surface level before you detect UXO at depth. So the most reliable ways of identifying UXO do require some form of intrusive work. The optimal way is cone penetration testing with a magnetometer on the tip of the sensor to look ahead, and whilst not providing a wide range of coverage, it provides a very high degree of confidence that you have cleared that zone. These things evolve but there has been no revolution.