MOTT MACDONALD

How do we deliver the skills needed to safely use advanced analysis software?

Creating earthquake-resilient assets.

Cutting 14 weeks from the delivery of Crossrail's deepest shaft.

Geotechnics

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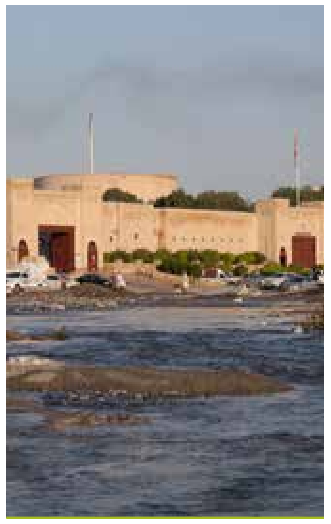


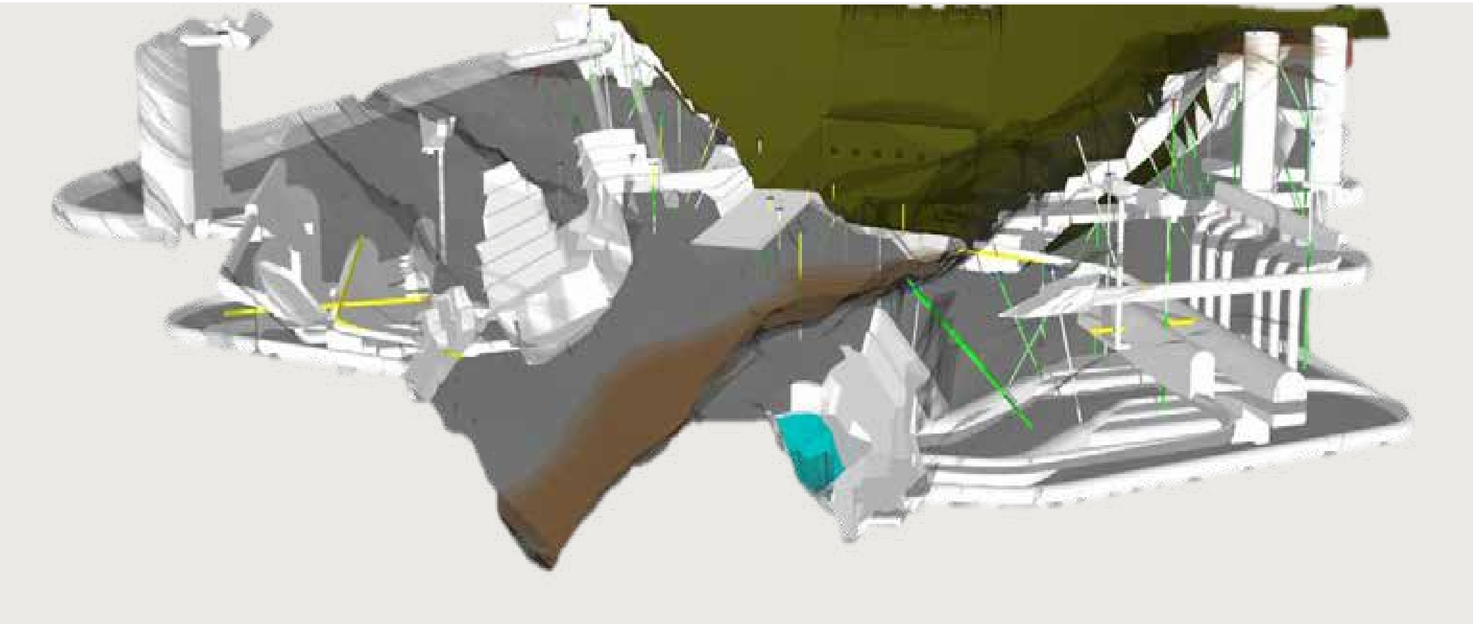
The heart of the matter

The ground is one of the biggest uncertainties in construction projects and while the latest analytical tools can provide accurate predictions of ground behaviour, we still need to get the basics right, says geotechnics practice leader Tony O'Brien.

Numerical modelling has developed rapidly in the last decade to become an integral part of almost every major project. These models can provide good predictions of ground behaviour, aiding decision making throughout planning, design and construction.

Knowledge gap
Unfortunately, site investigation methods and expertise have struggled to keep pace with developments in numerical modelling and this gap is widening. My keynote lecture at the 2016 BGA Fleming Award highlighted a key issue: the type of information being gathered, and how it's interpreted.

Conventional ground investigations tend to focus on measuring basic index properties. However, to realise the potential benefits of numerical modelling, reliable data on the ground's stiffness properties is essential.



Technical competence and checking
It's been shown that problems can often arise with numerical modelling because practitioners either lack the necessary competence to use the latest software or reliable input data is unavailable.

Fortunately, this knowledge gap is becoming better recognised. The EU is funding the Competency in Geotechnical Analysis (COGAN) project, which aims to stimulate improvements in technical competency.

Mott MacDonald's reputation for advanced numerical modelling using a range of commercial software packages and in-house developed models, led to our involvement in COGAN: we are the sole UK consultancy sector partner in the project.

We've also developed a bespoke 'ten steps' methodology for managing the implementation of numerical modelling, and we're helping project managers to use this technology more effectively.

Industry initiatives such as COGAN are vital if we are to ensure a coherent approach to minimising ground-related risks, maximising opportunities for innovation and delivering cost, time and carbon savings for our clients.

The latest analytical tools can offer significant benefits, but must be combined with a sound understanding of ground behaviour and the judgment of senior professionals.

Checks and balances
Geotechnics organisations must also have the correct 'checks and balances' in place when using the latest technology – be it analysis tools or ground investigation methods. This requires independent review by senior professionals at key stages of a project.

Geotechnics inputs throughout the project
There is no substitute for sound knowledge of the fundamentals of geotechnics and the systematic application of this knowledge throughout the project lifecycle.

As discussed in this magazine, geotechnics expertise can deliver significant benefits for our clients and society. We can help deliver projects quicker, safer and cheaper, while minimising use of scarce resources and environmental impacts. This knowledge can be applied from initial planning through to long-term asset management.

Powerful geotechnics

A deeper understanding of the geotechnical risks for hydropower projects is becoming more important as the number of suitable sites diminishes, says principal engineering geologist Antony Drake.

Installed hydropower capacity hit 1064GW in 2016, delivering about 16% of the world's electricity. Insatiable demand for power means many more GW of generation is yet to come.

There are three types of hydropower schemes, ranging from 100kW to more than 22GW capacity: 'run of river', where electricity is generated through diversion of some or all of the river flow with limited or no storage of water; 'storage', where power is generated through the release of stored water in a reservoir; and 'pumped storage', where water is recycled by pumping it back up to a reservoir, using excess electricity, to be released again when demand outstrips supply.

Renewed support for hydropower from the World Bank is helping to drive more sustainable development, with a trend towards run-of-river schemes with their reduced environmental and social impact. The benefit of being able to store energy produced by irregular and unpredictable renewable sources, or large capacity 'flat output' generators such as coal or nuclear, is also driving interest in pumped storage.

Complex challenges

By their very nature, these projects often have to be built in mountainous, inaccessible locations, with complex geology. And, along with the facility itself, there is a requirement for access roads (both for construction and for ongoing maintenance), surface or underground waterways, and transmission lines to take generated electricity to wherever it is needed.

Because each project is a 'one-off', exposure to factors such as geology, natural hazards or extreme weather means the already significant civil works costs are unpredictable and come with high risk attached. Success or failure of the scheme at the feasibility stage often rests solely on physical considerations.

Counter to this, and because of the high level of uncertainty, clients and their investors are understandably reluctant to spend large sums of money at the pre-feasibility and feasibility stages.

Geotechnics' key role

A key role for ground specialists, therefore, is to ensure clients recognise the size of the geotechnical risks (for example landslides that could cause issues during construction and operation). They must help clients understand the careful balance that must be struck between cost and value. It is usually a false economy to save on work to reduce geotechnical uncertainty, whether that is additional ground investigation or increased geotechnical design effort. Geotechnical baseline reports (GBRs) are being used increasingly in the hydropower sector to better define the allocation of ground risk between client and contractor. GBRs are becoming a critical aspect of overall project risk strategy and, clearly, need to be led by geotechnics specialists who are also contractually aware.

"A key role for ground specialists is to ensure clients recognise the size of the geotechnical risk and help them understand the careful balance that must be struck between cost and value."

Not a tick box exercise

Ground investigation should not be seen as a 'tick box' exercise. Quality data will determine the reliability of site selection and outline designs for dam foundations, tunnels and slope stabilisation – and ultimately the tender prices received.

The main geohazards need to be identified in the most cost-effective way. As ground investigations for hydropower are often difficult and expensive and data is sparse, remote sensing and mapping (covering rock mass characterisation, structural geological mapping, and geomorphological mapping) take on greater importance.

And, while physical constraints can be the driving force during feasibility, there is still a need to understand the social, political and environmental context of these schemes and the institutional, financial and economic regimes within which they are built and operated.

Honesty and professionalism

This, combined with honesty and professionalism, is key; telling a client their scheme needs major changes if it is to be built, potentially hitting their return on investment, may be difficult, but it can save time and money in the long run.

This is becoming particularly important as many of the 'prime' hydropower scheme sites have already been developed, and more marginal sites are being chosen.

Playing the long game

Geotechnics should be an integral part of a multidisciplinary approach to long linear infrastructure projects such as pipelines and transport links, says principal project engineer and associate Scott Kibby.

"The best approach is to have central coordination of the investigation process by geotechnical specialists who are part of – and can call upon the expertise of – a multidisciplinary team."

Infrastructure projects, such as new rail lines, roads and pipelines, present a range of challenges. Many of our projects in North America can stretch for hundreds of miles, traverse sensitive environments and pass close to (or through) built-up areas, attracting significant political and local interest.

When it comes to geotechnics, one of the biggest challenges is how to gather huge volumes of subsurface and groundwater data over great distances, in multiple environments and climatic conditions. This data needs to be accurate, high quality and targeted, to ensure value for money while meeting the project's geotechnical needs.

Central co-ordination

The best approach is to have central coordination of the investigation process, by geotechnical specialists that are part of, and who can call upon the expertise of, a multi-disciplinary team. Experience is, of course, crucial. Teams that have delivered these projects will understand their intricacies; they are vastly different from a single site investigation – however big the site.

For example, the work associated with land and access rights for infrastructure schemes is a common cause of considerable delay, as it often involves seeking approvals and permits from multiple third party landowners, solicitors, local and regional government, environmental agencies, and other statutory bodies. With multiple stakeholders, including the general public, central co-ordination will smooth the process, enabling potential issues to be identified early and mitigating the risk of unforeseen delays.

Fewer touch points means better communication

Having the entire investigation process managed by one consultant also means communication is simplified and improved. This is particularly beneficial at the outset, when clear communication is essential to assess project requirements; to evaluate design and construction options and to understand risks, costs and timescales.

Once investigations are underway, having a single point of contact for both the client and multiple fieldwork crews – who are often working remotely – means issues on site can be resolved quickly and efficiently.

Right, first time

By their very nature, long linear infrastructure projects will likely pass over a wide range of ground conditions, requiring a range of sampling and testing methods. Geotechnical data will be needed for an equally wide range of designs, from foundations, to earthworks and horizontal directional drilling, for example.

It is therefore important that the geotechnical team has a clear picture of the project's design needs. This will give focus to desk studies – to highlight potential areas of concern – and help in fieldwork planning, to ensure the information gathered is 'right, first time'.

High quality data is vital

It goes without saying that gathering high quality geotechnical data is vital for any project. For infrastructure schemes, with sampling points spread out along the route, it is important that traditional physical investigations (boreholes and so forth) are supported by thorough desk studies, aerial surveys, along with remote sensing techniques such as geophysics, GIS and LiDAR.

Using a common data environment and building information modelling (BIM) will also help decision-making throughout a project, not just during the ground investigation but through to construction and into operation and maintenance. BIM has been shown to improve collaboration, accelerate programmes and reduce environmental impact.

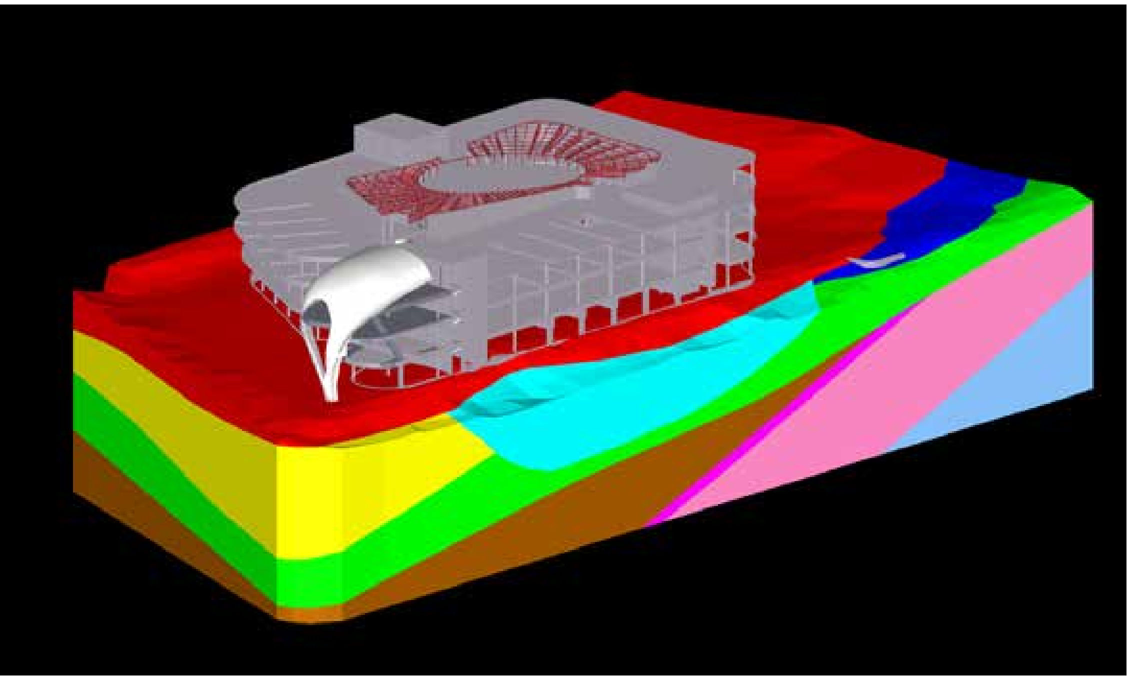
Cross-pollination

There is no denying that geotechnics plays a key role in building robust infrastructure efficiently and cost-effectively. However these projects require a different approach to 'single point' investigations if they are to deliver the maximum benefit.

The cross-pollination of expertise between different disciplines helps ensure decisions are made with a complete understanding of their implications, from the very outset of a project. This will result in high quality data being gathered, better design and, ultimately, better value for money.

Leaps and bounds

Collaboration between our geotechnics team and software company Aranz Geo has resulted in Leapfrog, a package that has slashed the time and cost of producing 3D ground models. Technical director Aine Martin explains.



BIM has become the accepted approach for major construction projects around the world. It incorporates many forms of data besides 3D models, but for ground engineers this functionality is powerful.

BIM represents a significant step forward in meeting the ground engineer's greatest challenge: visualising and mapping what lies beneath the ground with limited data. While it does not change the complexity of identifying hidden features between exploratory holes, 3D modelling does make things significantly easier to visualise. As a result, geotechnical risks can be better communicated earlier in the design process.

Integrating project design models with an accurate BIM ground model enables outline designs to be positioned on site, making it easier to analyse what's going on.

Ground investigation data can also be transferred to a BIM model in real time. Inputting geometry from the model directly into analytical packages enables further insights.

A ground model can be used to take off quantities for geotechnical structures and earthworks. Additionally, refining a BIM model with ground conditions uncovered during construction and as-built details of geotechnical structures benefits project operation, maintenance and decommissioning.

A leap forward

We've been working with New Zealand developer Aranz Geo to tailor Leapfrog, originally designed for the mining industry, to enable it to be used on civil engineering projects and feed directly into project BIM models.

Leapfrog has cut the time it takes us to produce ground models by 50% and reduced costs significantly – savings that can benefit project delivery.

Leapfrog is implicit modelling software that uses statistical mathematical interpolation – rather than the usual manual method of digitising data (explicit modelling) – to automate the drawing of surfaces such as boundaries and faults directly from geological data. This speeds-up the modelling process significantly and allows models to be updated automatically as information changes and new data is input.

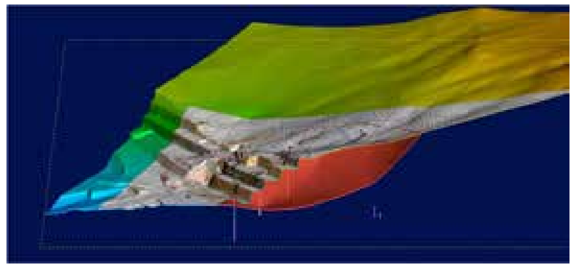
Implicit modelling relies on algorithms to determine how known data points are used to estimate unknown data points, hence creating surfaces. A great benefit of Leapfrog is that it can deal with very large datasets (more than 1M points) incredibly quickly on ordinary computer hardware.

Importing and exporting data drives collaboration and efficiency

Leapfrog's ability to work with different software packages to improve the speed and efficiency of modelling was demonstrated on the design of an underground station in Singapore.

The station's structural BIM model was inserted into Leapfrog, allowing the model to be interrogated to identify key risk zones and determine critical sections for geotechnical design. These sections could then be exported to specialist geotechnical analysis software.

The approach saved time and money and enabled better collaboration with the rest of the project team, which in turn improved the efficiency and accuracy of the model.



Instant updates help refine designs

Leapfrog instantly updates the model when new data is imported, which is particularly beneficial on major projects when new ground investigation data is gathered as work progresses.

We modelled a large underground cavern in Singapore covering an area of more than 1km². Investigations involved drilling more than 100 boreholes (some deeper than 200m), 3D seismic reflection and refraction surveys, and geotechnical testing to determine rock parameters.

Leapfrog enabled the complex geological conditions to be visualised and a deep weathering profile, intrusions and faults to be identified. This had a direct bearing on the final depth and orientation of the cavern and, by including geotechnical parameters in the model, it was possible to create 'zones' to predict the type and amount of rock support that would be needed.

Without Leapfrog, the depth of our understanding of the site would have been significantly diminished.

Historic data highlights risks earlier

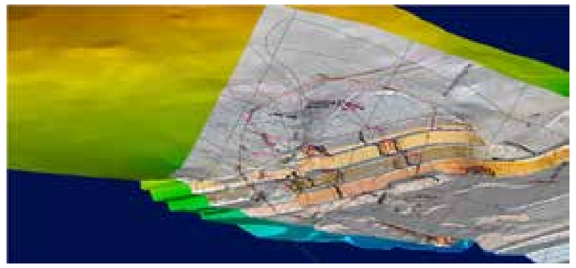
Leapfrog can incorporate historic maps and sections in its models to help verify existing data and highlight potential ground risks very early in a project before ground investigations have begun.

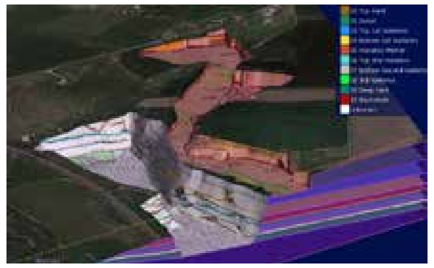
Once an initial model is in place, BIM becomes instrumental in designing ground investigations. Engineers can use the model to identify the best locations for exploratory holes. With these positioned in the model, it is easy to take off quantities and calculate ground investigation costs. Setting-out data can then be fed directly into surveying equipment or extracted as 2D drawings.

In Sheffield, we worked with mapping and data provided by the British Geological Survey and the Coal Authority to develop high-quality geological models that included historic opencast mining.

50%

cut in modelling time





Leapfrog allowed us to visualise the complex geology and share this with the client. Not only were communications improved but it also meant we could focus the ground investigation on areas where it was most needed.

Driving efficiency, saving time and money

When we started working with Aranz Geo, the aim was to improve our 3D geological modelling capability and to introduce a uniform modelling standard across the business, allowing us to include geotechnics fully with our BIM Level 2 project deliverables.

Leapfrog is now used by our offices worldwide and is rapidly becoming our global modelling software of choice, allowing teams to collaborate easily on a national and international scale.

The quality of the models has also increased significantly and can be benchmarked, audited and verified to meet our quality assurance obligations.

The benefits of BIM for quantifying, communicating and managing ground risk is becoming recognised by clients both in the public and private sector, but time and cost are often a barrier to its use.

Software such as Leapfrog opens up these benefits to many more projects than ever before, improving efficiencies and reducing the time and cost of modelling.

Since working with Leapfrog we have seen a 50% cut in the time taken to produce 3D ground models and a significant reduction in costs, compared with traditional approaches – savings that can be shared with our clients.

Rising problem

Urban development not only puts significant strain on water resources but is also leading to rising groundwater in many cities around the world, says technical director Peter Sharp.

There is no doubt that, as the world's urban population continues to grow at an ever-faster rate, there will be increasing pressure on land and water resources. What is perhaps unexpected is the recent rise of groundwater levels beneath cities, which poses risks to human health, property and infrastructure.

A global issue

Of course, the issue of rising groundwater is nothing new; the decline of industrial activity in cities in the developed world has led to groundwater levels recovering as water abstraction has reduced.

In London, for example, groundwater was 90m below the surface in the 1960s but has risen steadily ever since, threatening to flood parts of the London Underground. As a result, abstraction wells are now needed to keep the water table below tunnels and deep foundations.

And in arid regions such as the Middle East, rising groundwater beneath cities is a major issue, causing damage to structures and services and posing a risk to public health.

Complex reasons

The reasons for rising groundwater levels are complex. Urbanisation means naturally permeable ground is covered with impermeable surfaces such as roads, car parks and buildings themselves, which can reduce surface evaporation, additionally, basements, tunnels and foundations can block groundwater flow. After heavy rainfall, storm drains can overflow, increasing the burden on rivers and natural watercourses, and water used to irrigate parks and gardens can infiltrate the ground.

But the biggest cause of rising groundwater is leaking water and wastewater infrastructure: from potable water supplies, to district cooling systems, septic tanks, soakaways, sewers. This is due to a combination of poor design, a lack of maintenance and ageing assets, plus the fact that many systems are having to cope with flows much greater than originally envisaged.

Geological and hydrogeological factors

Of course, geology and hydrogeology play leading roles. Groundwater level is influenced by a number of factors, including the thickness and permeability of the soils above basement rock (and the nature of the rock) and also by topography – steeper slopes at higher elevations do not allow as much ponding of water as gentle slopes or flat areas.

Effects on development

For geotechnical designers, the presence of water means the shear strength and bearing capacity of soils are reduced. There is also increased lateral pressure on basement walls and settlement of buildings can occur.

A key challenge for the Middle East is the occurrence of near-surface weakly cemented, loose and partially saturated sands that are susceptible to collapse settlement if they become wet due to rising groundwater. In some cities, we have used remote sensing techniques, such as LIDAR, to identify areas at risk of settlement, enabling planning authorities to ensure developers take these risks into account.

“Rising groundwater can lead to multiple issues for infrastructure and planned developments, including flooding of inadequately waterproofed basements, settlement and increased uplift pressure on buildings, utilities and other underground structures.”

Rising groundwater can lead to multiple issues for infrastructure and planned developments, including flooding of inadequately waterproofed basements, settlement and increased uplift pressure on buildings, utilities and other underground structures. Long-term issues, such as the deterioration of concrete used in foundations and basements, can also occur due to high levels of sulphate or chloride in groundwater.

Effects on human health

Rising groundwater also poses a risk to human health, with groundwater becoming contaminated through leaks from sewers, septic tanks and soakaways, and from industrial wastewater, for example. Contamination can enter potable water supplies through cracked pipes and leaking tanks, flowing into rivers and natural watercourses and also entering the food chain. Ponding of surface water can attract disease-carrying insects, such as mosquitoes.

Dealing with rising groundwater

Engineers have a range of measures at their disposal to deal with rising groundwater. These include dewatering wells, improved waterproofing of basements, deeper foundations, construction of stronger underground structures to resist settlement and uplift, and the use of sulphate- and chloride-resistant concrete.

Prevention is better than cure, however: repair and remediation of subsurface structures damaged by groundwater is complicated and expensive. Thorough ground investigation, incorporating an assessment of the hydrogeological regime, is essential.

It is also important that cities have comprehensive water management plans in place. As well as ensuring infrastructure is resilient enough to cope with increasing demand (and climate change) and is well maintained to reduce leakage, these could include planning and construction regulations, plus enforcement by authorities, to ensure groundwater issues are considered appropriately both in the design and operation of developments.

With more and more of us living in cities, the issue of rising groundwater is not going away any time soon. The importance of a complete understanding of the water balance and the ground is crucial to ensuring buildings and infrastructure remain serviceable and safe.

There's a storm coming

Considering climate change in seismic design is crucial to help ensure buildings and infrastructure remain resilient to future shocks, says senior principal engineer Barnali Ghosh.

It's widely accepted that climate change is playing a role in the increasing frequency and severity of natural disasters.

Clearly, climate has no influence on how often earthquakes occur, but the ability of a building or piece of infrastructure to withstand a seismic event could be compromised by ongoing and intensifying climate change. This is not just a 'developing world' risk either: structures are vulnerable even if they meet the latest seismic design codes.

The major principle of earthquake design is to introduce resilience in buildings. Typically, we achieve this by designing the foundations in such a way that, during seismic incidents, the superstructure is affected before the substructure, avoiding damage below ground level.

There are a number of potential risks. Rising sea levels combined with heavier and prolonged rainfall can result in groundwater levels rising, making soil more prone to liquefaction – a key cause of damage in many earthquakes. Shallower water tables combined with increased humidity can make foundations and superstructures more vulnerable to corrosion, reducing their resilience. And higher rainfall can increase porewater pressure in soils and rocks, making slopes more vulnerable to landslides and putting assets at risk.

Urban vulnerability

Cities are particularly vulnerable, as they tend to be in coastal areas threatened by floods, storms and other natural hazards, and this vulnerability is likely to increase, as urban populations grow over the next 30 to 40 years.

Over the past 30 years, an estimated US$3.8tn has been lost through recurring disasters – equivalent to one third of all the money spent on development over that period. A growing concentration of people, assets and infrastructure in urban areas means that the potential for loss is likely to be much higher in the future.

We will have to construct taller and taller buildings to deal with the squeeze on development space. These structures will be subjected to higher lateral loading in more frequent storms, increasing the risk of overturning, should an earthquake hit at the same time.

Integrated assessment vital

It's vital that the risks arising from seismic events and climate change are assessed in an integrated way to ensure resilience. Engineers, planners and owners need to consider an asset's purpose, lifespan and reliance on infrastructure to prevent failure.

In particular, we need to recognise the impacts of climate change on geotechnical characteristics, soil-structure interaction, and structural loading, to help us to create the next generation of earthquake-resilient assets.

"This is not just a 'developing world' risk: structures are vulnerable even if they meet the latest seismic design codes."

Secure storage

Underground storage of natural gas is vital to the UK's future energy security, says associate geotechnical engineer Nicholas Haynes.

"Obtaining a complete geological picture of the salt deposits and surrounding ground is a key part of the planning process, requiring a wide range of expertise."

It's estimated that by 2025 about 75% of the UK's natural gas needs will be met by imported gas. Less flexible supplies could lead to shortages, exposing consumers to price fluctuations in volatile international gas markets.

Smoothing out the bumps

Storing large volumes of gas is one way of smoothing out these 'bumps' but the UK has very little capacity. This raises significant issues for the country's energy security.

Underground gas storage may be the answer. There are two main options: pumping gas into depleted oil and gas reservoirs beneath the North Sea or creating caverns to store gas in onshore salt deposits.

Oil and gas reservoirs are certainly a viable option, but they are expensive to develop (being offshore) and it takes time to retrieve the gas, making sudden spikes in demand more difficult to meet.

Salt solution

Salt cavern storage is perhaps more attractive. These bodies are relatively shallow (lying at depths of between 300m and 1000m) and allow gas to be stored at pressures similar to that of transmission. This enables gas to be pumped out quickly to meet daily fluctuations in demand.

Caverns are formed by drilling down to the salt deposits and then pumping in water to dissolve the salt. The brine created is pumped out, leaving a teardrop-shaped cavern, with the borehole at its centre, through which the gas is pumped.

Because salt is impermeable, the caverns are unlined: the boreholes are encased in multiple cemented casings to ensure impermeability is maintained to the surface. Gas within the caverns has to be stored at a higher pressure than the hydrostatic pressure of the surrounding ground (to prevent the cavern collapsing) but not so high that it causes cracking in the rock mass, which could allow the gas to escape.

Obtaining a complete geological picture of the salt deposits and surrounding ground is a key part of the planning process, requiring a wide range of expertise, such as rock mechanics, geology, seismic assessment, geotechnical design and groundwater modelling.

Boosting the UK's gas storage capacity

Such was the challenge facing Halite Energy, a US firm that hopes to develop a major underground gas storage facility in Lancashire. Its Preesall Gas Storage Scheme will see 19 underground caverns built, giving a total storage volume of about 900Mm^3 and boosting the UK's gas storage capacity by 20%.

The 60m to 100m diameter, 60m to 330m high caverns will be formed at depths of between 300m and 740m in the Preesall Salt formation, comprising halite deposits interbedded with mudstone.

A major challenge will be to build the facility next to the environmentally protected Morecambe Bay and Wyre Estuary and close to an historic, and much shallower, abandoned underground brine field and salt mine.

Drawing conclusions

We were brought in as geological liaison to draw conclusions from more than 50 technical reports that could be used in support of Halite Energy's Development Consent Order application, and to carry out risk assessments for the construction and operation of the facility.

We worked with the expert subsurface team, including the British Geological Survey, GeoStock Entrepose, Hanover University, Imperial College and Halite's deep oil and gas geologists, to produce geological summary reports and to carry out quantitative risk assessments, including for seismic events and subsidence.

Our work was used as part of the public consultation process to give the local community confidence that Halite Energy would mitigate the risk of gas leaks and environmental harm to the area.

We also developed an investigation, monitoring and maintenance strategy to assess the potential risks and impact of the nearby abandoned salt mine and 110 brine wells on the proposed site.

Co-ordinated pay-off

This co-ordinated approach paid dividends: after being rejected twice before we became involved in the project, Halite Energy was finally granted development consent in 2015. The project is now in preconstruction, with construction due to start before 2020.

Focus on resilience

Performance-based seismic design seeks to understand how ground and structures move and deform during earthquakes to deliver more-resilient infrastructure, says principal engineer James Scott.

Performance-based design has grown in popularity as a way to deliver more-reliable structures. Rather than assuming stiff structures are more resilient, designs are based on safely dissipating earthquake energy via controlled ground displacement and movement-tolerant structures.

Designers consider the stress-strain behaviour of the ground and the deformation mechanisms at play, and link these to the desired performance of structures. This allows owners to understand earthquake risk as a part of design, enabling them to make decisions that result in more-resilient infrastructure.

The Port Mann/Highway 1 Improvement project
This was one of the first projects in Canada to adopt a multilevel, performance-based seismic design approach.

The CA$2.5bn scheme, completed in 2015, formed the largest part of British Columbia's Gateway Programme, a regional transportation plan that aimed to improve the movement of people and goods, and transit throughout Greater Vancouver.

The onshore part of the project, costing CA$1.6bn, involved widening of 37km of highway, upgrading and reconstructing 15 interchanges, building 39 new bridges, rehabilitating and seismically retrofitting six more, plus construction of 25 lightweight fill expanded polystyrene (EPS) embankments.

Vancouver is close to the Cascadia Subduction Zone, where the Juan de Fuca plate dives beneath the North American plate.

To address earthquake risks in this highly seismic area, the Ministry of Transportation and Infrastructure set minimum requirements for post-earthquake performance, including service levels and damage thresholds, for three levels of ground movement (based on 1:475, 1:975 and 1:2475-year earthquakes).

"A crucial part of performance-based design is to establish quantitative relationships between engineering design parameters and the owner's performance objectives."

Taking a performance-based design approach
A crucial part of performance-based design is to establish quantitative relationships between engineering design parameters (strains in concrete, ground displacements and so on) and the owner's performance objectives.

The design for PMH1 had to consider a magnitude 8.2 subduction type earthquake, similar to some of the world's largest earthquakes including Chile's 2010 (8.8) Maule earthquake and Japan's 2011 (9.1) Tohoku earthquake.

There was significant potential for liquefaction of loose to compact sands during an earthquake of this size, which could result in post seismic-settlements, lateral spread of the highway embankments and, ultimately, catastrophic collapse.

To reduce potential ground movements and meet performance objectives, we identified that more than 625,000m³ of ground improvement would be needed. This included vibro-replacement stone columns to densify and reinforce potentially liquefiable soils and ensure stability of embankments and walls, plus jet grouting and cement bentonite slurry wall panels to mitigate the risk of lateral spread beneath bridges.

Performance-based design called for sophisticated seismic analysis to provide estimates for the engineering design parameters. This included both structural forces and examination of liquefaction and ground displacement hazards.

Advanced numerical modelling was used to assess the risk of liquefaction with the onset of strong ground motions. The modelling indicated that the extent of liquefaction for large magnitude events was less than that determined from conventional linear analysis. This allowed significant cost savings.

Performance-based seismic design requires careful consideration of the return period at which there is the potential for the onset of liquefaction and significant ground movements, as this can represent a step change in the structure's performance.

Given how important this was for PMH1, a series of advanced laboratory tests were carried out on samples of silty sands and silts taken along the route to help understand the potential for liquefaction and the requirement for ground improvement. This testing confirmed that the silty sands had greater resistance to liquefaction than indicated by empirical methods.

The benefits of performance-based design
PMH1 demonstrates how performance-based design, along with a better understanding of seismic hazards and increased sophistication of seismic analyses, gives clients an insight into the reliability of their infrastructure and enables us to manage seismic risk more effectively. This approach means infrastructure should perform better and maintain functionality after an earthquake.

Other geotechnical challenges for PMH1
In some areas, soft compressible deltaic sediments included deep deposits of peat over soft alluvial silts and clays. The high groundwater level and thickness of these deposits meant it was not always practical to remove and replace them. About 200 surcharges were carried out and more test surcharges performed to help understand if treatment would meet programme requirements and long-term settlement criteria.

In some areas, surcharging was not possible. In these cases, EPS was used to reduce the load of new structures and post-construction settlement. The added benefit is that EPS structures perform well during earthquakes. Twenty-five EPS embankments were built, some up to 14m high, which is believed to be the largest amount of EPS ever used on a North American infrastructure project.

EPS alone was unsuitable in areas where the risk of flooding was high as the material's self-weight meant there was a risk of the structures becoming buoyant. In these instances, EPS was supported by timber pile load transfer platforms above the design flood elevation.

25
EPS embankments

Water water everywhere

The shift to design and build in the UK water industry is driving value for money for water companies and delivering benefits to consumers. Geotechnics has a major part to play, says principal geotechnical engineer Mark Edmondson.

The UK water industry's sixth Asset Management Period (AMP6), which began in March 2015, saw many water companies adopting design and build for delivery of their infrastructure construction and maintenance contracts.

The attraction of design and build

In previous AMPs water companies typically used their own design teams or employed consultants to carry out design before going out to tender with contractors. But design and build's ability to accelerate and give certainty to construction programmes, drive innovation and save time and money has proved too attractive to ignore.

Design and build companies, such as Mott MacDonald Bentley, have established themselves to deliver these programmes of work, appreciating that a strategic focus, effective communication and a flexible approach can help build relationships with clients. Design and build brings benefits to these companies too, giving them the freedom to use alternative solutions, while meeting project requirements.

Collaboration to the benefit of all

Collaboration is central to success, with a constant exchange of ideas and information between the design, contract management and site teams being crucial.

For geotechnical engineers, this joined-up thinking gets their voice heard and leads to cost savings through more-focused ground investigations that drive more-efficient overall project design via early mitigation, or, indeed, removal, of key ground risks.

Geotechnics is a key issue. The water sector's ageing assets require repair, maintenance and modernising to meet growing demand. We are regularly called upon to assess the stability of earth dams and the risks of seepage both through and beneath them, to design upgrades of spillways and to expand water and wastewater treatment works.

Money well spent

Water companies generally appreciate the importance of good-quality geotechnical data. Investigations are about understanding and mitigating ground risk, so a full picture of the ground can mean temporary works are minimised, foundations optimised, costly groundwater control measures avoided and earth structures made more robust.

Embedding geotechnics

Because geotechnical design is embedded in the design and build process, it can mitigate risk and avoid abortive design costs. Design and build is also embracing use of BIM, further improving workflows, data handling, construction processes and programmes, and driving more efficiencies.

Back on track

An innovative observation-based verification approach cut 14 weeks from the construction of the deepest shaft on Crossrail, ensuring previous delays on site did not hinder the progress of tunnelling machines. Technical director Imran Farooq explains.

When it fully opens in 2018, Crossrail (which will operate as the Elizabeth Line) will have 38 stops, including nine new underground stations in central London. Some of these involved challenging geotechnical engineering.

Liverpool Street Station challenges

Liverpool Street Station will eventually handle 26M people a year. Designed by Mott MacDonald, it has two platform tunnels spanning between ticket halls at Liverpool Street and Moorgate with links to London Underground and mainline rail routes.

Moorgate Station ticket hall is being enlarged to create an integrated western ticket hall with two banks of escalators taking passengers to the new platforms 35m below street level. These, along with plant rooms, are contained within a 42m deep shaft in a very tight site bounded by the Metropolitan Line to the north, Northern Line tunnels to the east and about 50 buildings, some of them listed.

With the shaft's east wall less than 5m from the northbound tunnel of the Northern Line beneath Moorgate, limiting deformation to protect nearby buildings and tunnels governed design. In general, the target was to limit horizontal wall movement to no more than 45mm, but for the east wall this was set at a maximum of 30mm. We designed the shaft as a irregular polygon in plan, roughly 35m by 35m, formed by 1200mm thick diaphragm walls. It was constructed top-down, with seven reinforced concrete ring beams installed to stiffen it.

"The observation-based verification process reanalyses the design using real-time monitoring and 3D numerical analysis of soil-structure interaction, ground movements and movement of nearby tunnels and buildings."

Crossrail's westbound running tunnel meets the shaft between the lowest ring beam and the 2m thick base slab 12m below. The original plan was to use a combination of two temporary cross walls and the early build of part of the station's internal structure – a pair of 3m wide, 1.5m deep slab strips – to restrain east-west movement of the walls in the deepest part of the shaft.

Staying on the critical path

The new station was on the critical path for the completion of Crossrail's central tunnelled section.

But extracting the foundations of the six storey 1970s concrete-framed building previously on the site took much longer than anticipated, delaying the start of shaft construction by 11 months.

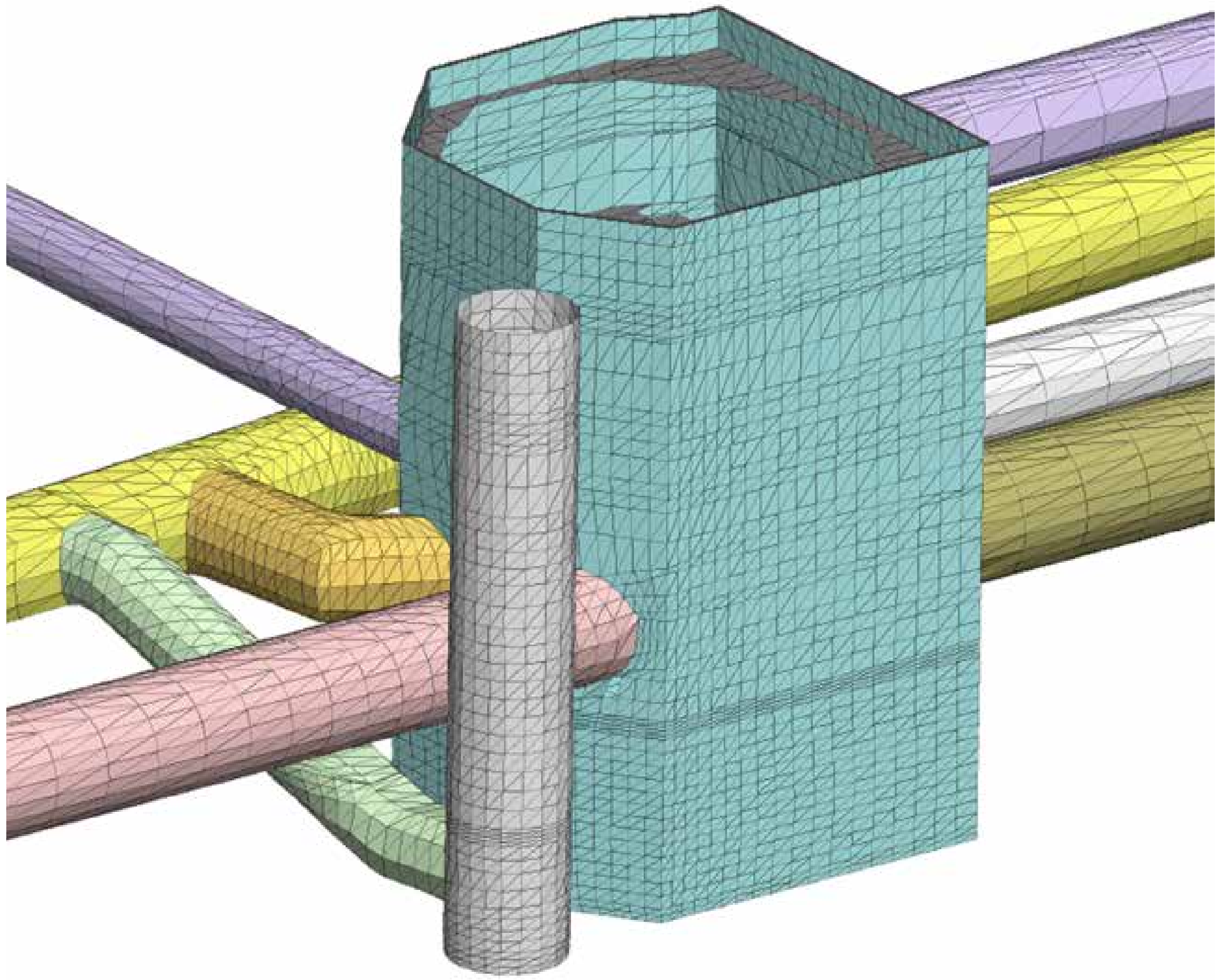
This made it highly unlikely that contractor Bam Nuttall/Kier Construction JV would complete the shaft before the TBM building the westbound tunnel arrived.

A new verification process

To meet the deadline, a new approach was needed. We proposed an observation-based verification process, reanalysing the design using real-time monitoring and 3D numerical analysis of soil-structure interaction, ground movements and movement of nearby tunnels and buildings.

The aim was to refine and accelerate the construction sequence by reducing the number of excavation stages and omitting temporary support during each stage and, more importantly, in the deepest part of the shaft.

This was the highest priority, as installing temporary support would have taken several weeks and severely restricted the working area for casting the base slab. Props would also have had to be removed to allow the TBM to pass through the shaft. Our verification process differs from the more conventional observational method (OM) as several temporary support measures are included in the design and only omitted if observations and analysis confirm they are not needed. This provided a higher level of assurance to external stakeholders, than conventional OM.



"Our approach was extremely good news for Crossrail, as it allowed the shaft to be completed ahead of schedule, cutting 14 weeks off the original programme."

In the case of the Moorgate shaft, the plan was to use temporary props at three levels. If these measures were needed, the programme would be unaffected. If they could be omitted, then immediate time savings would be made.

Real-time monitoring

Along with close collaboration between contractor, designer and client, the verification process relied on high-quality, real-time monitoring of diaphragm wall movement, settlement, pore pressures and heave within the excavation, and the use of a non-linear ground model built in FLAC 3D which was recalibrated throughout construction based upon observed behaviour.

The non-linear model – which we had also used on the design of sprayed concrete lined tunnels for Crossrail Contract 121 between Bond Street and Whitechapel – uses key ground parameters based on field and laboratory data, plus back-analysis of tunnel construction on our previous projects at Heathrow Express and King's Cross Station.

Real-time monitoring was carried out using surveying and data from instrumentation already in place to monitor the diaphragm wall and movement of neighbouring above- and below-ground structures. This included inclinometers, Shape Accel Arrays, extensometers, vibrating wire piezometers, standpipes and strain gauges.

Getting to the point

Three verification points (VP1, VP2 and VP3) were set at depths of 19m, 26m and 30.5m respectively. At each point, the FLAC 3D model was updated to incorporate the as-built details and used to predict ground behaviour for the rest of the excavation, the geological conditions likely to be encountered and to revise the ring beam design to match actual conditions. The team could then assess whether temporary support was needed and the mitigation measures should movements approach trigger levels or if excavation stages could be combined.

There was a reasonable match between predicted and monitored movements at VP1, with real movements generally lower than predicted – although the eastern wall had moved more than was first thought due to permeation grouting carried out next to the shaft. Despite this, it was decided that it was safe to omit one level of props.

At VP2, 7m below, further analysis – including the effect of clay inclusions in the diaphragm wall panels and the permeation grouting – concluded that a second level of temporary props could be omitted and two construction stages could be combined. This allowed a continuous dig with two ring beams cast at once, reducing construction time.

At VP3, the results showed that potential effects on the Northern Line tunnels due to shaft excavation-induced movements were minimal. In fact the cumulative effect of the shaft excavation was a short-term settlement of less than 10mm. More refined predictions at VP3 also showed that movements of the east wall had reduced from VP2, allowing all the temporary props to be removed.

All of this was extremely good news for Crossrail as it allowed the 1800m^3 concrete pour for the base slab to be completed ahead of schedule and cut 14 weeks off the original programme, so there was no delay to the TBM's drive westward to Farringdon.

Not hazarding a guess

Ground modelling, geohazard assessment and risk analysis need to consider a wide range of social, economic and political factors, says engineering geologist Chris Arnold.

The risk of landslides, subsidence, faulting, earthquakes and extreme weather events can all influence the design, construction and management of infrastructure, especially in regions such as the Caribbean.

The interplay of these risks – along with due consideration of social, economic and political factors – should form the basis of any geohazard and risk assessment.

Modelling to manage risk

A comprehensive ground model can enable better decision-making and reduce ground risk in the planning, design, construction and operation of an asset. The earlier the risk is understood, the better it can be managed and the wider the benefits.

Cheap computing power, access to satellite and drone imagery, and improvements to remote sensing techniques – such as LiDAR mapping and photogrammetry – means that getting a detailed understanding of morphological processes and producing an accurate ground model is becoming faster, easier and very cost-effective from desk studies.

Multiple benefits

There's no substitute for having geotechnical engineers and geologists on the ground, but desk studies can help pinpoint areas of interest and provide a focus for physical mapping and intrusive ground investigations. Use of terrain evaluation and geomorphological mapping techniques has great value at this stage.

This makes subsequent investigations more efficient and potentially more cost-effective, particularly for large study areas. Increasingly, field data is also being gathered digitally, so ground models can be updated and verified quickly and easily.

Ground models can help refine route selection, create risk maps, enable the development of designs and recommendations for specific ground conditions, and identify suitable materials for earthworks.

For asset operational resilience, ground models can aid development of management strategies by presenting relevant geohazards clearly. Landslides, for instance, can be described in terms of frequency of failure. This approach can aid understanding of the vulnerability of elements at risk in terms of impacts such as the severity of failures and their knock-on effects.

Taking a wider view

These effects can be financial, social and political, and it's important to understand how asset failure can affect local communities, public safety or economic performance. This will help decide if it's better to take a proactive approach and provide preventative measures or adopt a reactive stance, waiting until failure occurs and carrying out remedial works.

Severe weather events are becoming more frequent and can have profound effects. Prolonged rainfall can increase porewater pressure in soils and rocks, making slopes more vulnerable to landslides – a serious issue in regions affected by monsoons, hurricanes and tropical storms. Rainfall intensity and surface water flow during storms increase the risk of wash out erosion.

Complete understanding

Ground engineering professionals also need to get 'under the skin' of asset owners and local stakeholders to fully understand the non-technical implications of asset failure beyond just identifying ground hazards. With increased use of marginal land for urban development and pressure on existing and future infrastructure, the need for comprehensive understanding of geo-hazards and associated risks in a wider context is sure to grow.

Deep and meaningful

Innovative geotechnics employed on Singapore's Marina Coastal Expressway should ensure future deep excavations in the city state can be built quickly, economically and safely, says geotechnical director Nick Mace.

"Deep excavations in Singapore have to comply with strict limits on lateral deflection of retaining walls – just 0.5% of excavation depth."

The sudden and fatal collapse of a cut and cover tunnel at Nicoll Highway in 2004 demonstrated the huge power of the forces at work in the ground and the potential danger of design or construction errors, not only in Singapore but around the world.

Strict limits

Following the collapse, Singapore's Land Transport Authority (LTA) improved the safety of deep excavations by setting out requirements for temporary works, including geotechnical parameters, retaining wall design and ground improvement.

Since then, projects have had to comply with strict limits on the lateral deflection of retaining walls – just 0.5% of the excavation depth. Before Nicoll Highway, two to three times that amount was allowable, providing it was demonstrated that deflection would not have a detrimental effect on surrounding structures.

Marina Coastal Expressway

This was the challenge faced by contractors building the Marina Coastal Expressway (MCE): the maximum deflection was limited to just 75mm over the 60m wide cut and cover excavation's 15m deep temporary retaining walls.

MCE is a 5.1km long, dual five lane highway, linking expressways in east and west Singapore with the new downtown area in Marina Bay. The route crosses an area consisting of 30-40m of under-consolidated marine clay with the consistency of toothpaste sandwiched between firm Old Alluvium below and 15m of reclaimed fill above.

Construction involved installing temporary longitudinal retaining walls, excavating to the final depth and casting a base slab, permanent side walls and a roof. The marine clay is highly plastic and flows when loaded, so robust temporary works were required to reduce structural movements and to limit heave in the base of excavations.

To ensure deflections stayed below the 0.5% limit, the LTA specified two layers of jet grout columns beneath the base of the excavation, anchored at depth by bored piles. The temporary side walls were formed by a combination of soldier piles and sheet piles, with the former toed 2.5m into the Old Alluvium. Five layers of temporary propping were installed 3m apart.

We worked with contractors Samsung and Ssangyong on three of the six MCE contracts. Samsung built Contracts 483 and 486, which included 1750m of tunnel and ventilation buildings. Ssangyong was responsible for Contract 482, comprising 500m of lowered road, 500m of tunnel, a stub for a future tunnel and, beneath the MCE, a short section of light rail tunnel for the planned Mass Transit Railway North-South Line.

20%
pile diameter reduction

36%
saving in concrete

Value engineered ground improvement
Our engineers saw an opportunity to save cost and add value for LTA by using deep cement mixing (DCM) instead of jet grouting to provide ground stability below the cut and cover tunnel.

We examined the performance of both options and concluded that DCM would work better as the slender drill strings used for jet grouting would be up to 25m long, making them liable to deviate from their designed path. This presented a risk of localised weaknesses in the jet grout slabs.

The larger diameter augers used in DCM were stiffer and so could be controlled more closely, with the result that the quality of ground improvement was likely to be higher. The only issue was that just one DCM layer could be formed. Fortunately, our modelling demonstrated it would perform as well as two jet grout layers.

The bored piles anchoring the improved ground layer were installed at 6m centres. Previous projects had only considered pile performance in compression. However, by making the piles stiffer we predicted heave could be reduced by increasing their tension capacity.

This was achieved by adding reinforcement but, to avoid unnecessary use of steel and resulting cost, forces acting on every one of the 2500 piles across the three contracts were analysed to optimise the amount of steel needed in each.

The combined performance of the DCM layer and the piles meant its thickness could have been reduced to 8m. However, a 10m thick slab enabled pile diameters to be cut by 20%, saving 36% in concrete. This value engineered solution was quicker, cheaper and safer than the original design.

Stronger retaining walls cut construction time
The solution also involved constructing retaining walls using 1.2-1.5m diameter pipe piles instead of the sheet and soldier pile combination.

Pipe piles were far stiffer, making it easier to comply with the LTA's very tight wall deflection criteria. Alternating short and long piles were used, with the longer piles embedded 2.5m into the Old Alluvium. This approach was faster and simpler as the Old Alluvium acted as casing to allow the pile to be bored and concreted.

An added bonus was that piles could be removed once construction was finished. Because jet grouting had to be used to seal the gap between the retaining walls and the DCM slab, it would have been very difficult, if not impossible, to pull the sheet piles. Circular pipe piles, on the other hand, are far easier to extract.

Fewer props save time and money
The pipe piles' structural strength would, in theory, have allowed all but one layer of temporary props to be omitted. However, this would not have been acceptable to LTA, so instead we proposed cutting the propping to just two levels. The first was just below ground level while the second was installed at mid-height, 7m down, with deep level restraint provided by the DCM slab.

Omitting each single prop layer saved SG$10M, delivering overall project savings of SG$90M over the three contracts. The approach was also faster and safer as fewer props had to be installed.

Productivity was further improved by creating more working room, allowing equipment to be moved around more easily. This also made casting the concrete base slab easier, as there was 7m clearance between the slab and the lowest props.

Once the slab was cast, the lowest level of temporary propping was removed, allowing the permanent reinforced concrete side and central walls to be created in single, full-height pours. This was a much faster approach than the originally planned 3m high pours that would have had to be employed with four or five levels of props. There were also fewer joints, making the walls stronger and more durable.

Super beam solves junction challenge
C482, built on a curving alignment, was complicated by the inclusion of a stub-tunnel branching off from the MCE at 45°, plus a second tunnel passing underneath at 45° in the other direction.

Walls on the MCE were typically parallel, 60m apart, but at the junction this distance increased to as much as 135m, making it difficult, if not impossible, to prevent props deflecting. An added complication was that loads from the diverging walls would generate longitudinal forces in the retaining system.

The solution was a reinforced concrete 'super beam' following the line of the main MCE retaining wall. This beam divided the excavation into manageable spans and collected longitudinal load from the props, transferring the out of balance thrust into the retaining wall.

A drain on resources

Drainage plays a vital role in ensuring infrastructure operates effectively, but for too many years this asset has been neglected, says principal engineering geologist Chris Power.

Highways England has estimated that 70% of earthworks failures on its network are due to inefficient drainage. London Underground has also identified drainage issues as being responsible for the vast majority of significant earthwork failures on its rail sytems.

Missing link

For many years, the link between drainage assets and overall asset management was either unrecognised or ignored. Since then, a patchwork of repairs has been carried out, but this lack of understanding about the connection between drainage, slope stability and asset performance has led to long-term problems.

Ensuring drainage operates effectively is one of the most important factors in maintaining infrastructure earthworks. It can affect the performance and working life of road pavements, track beds, embankments, cuttings and many other structures.

Difficult assessment

All asset management activities start with the capture of key descriptive data on the asset inventory and condition. Ensuring the quality of this data is vital and requires robust asset inspection methodologies. Unfortunately, assessing drainage can be very challenging as most of it is hidden and below ground. A lack of construction records means drainage is often unknown. Even when it is located, it can be tough, slow and expensive to survey. And limited access means it's often difficult to know the full extent, condition and performance of drainage systems.

As a result of increasing recognition of this issue, we have worked with infrastructure owners such as Highways England and Network Rail to help them develop methodologies for assessing drainage as part of their asset management strategies.

Dealing with problems on the roads

Drainage is a safety-critical aspect of highways design. It prevents flooding of the carriageway, enables pavement structures to perform for longer with less maintenance, and ensures embankment and cutting slopes remain stable.

We developed the GIS-based Highways Agency Geotechnical and Drainage Data Management Systems (HAGDMS and HADDMS), which bring two key interrelated asset types together in one place.

This reflects the way our Civils Asset Management team works: we can draw on our knowledge of cross-asset interdependency between geotechnical, drainage and structural assets, as well as our understanding of materials behaviour.

HAGDMS is the national repository of data related to the 50,000 earthworks on England's strategic road network, holding all inspection records and an archive of more than 13,500 geotechnical reports.

HADDMS holds drainage information from numerous sources, including as-built drawings and detailed CCTV surveys, and records all flooding incidents on the network.

Although both systems provide workflows for geotechnical and drainage asset management processes, and despite Highways England recognising there was a relationship between the performance of drainage and the condition of other assets, until recently it was not possible to quantify either the impact or the likelihood of flooding.

In an effort to solve this issue, we developed a series of 'risk bow-tie' diagrams that illustrate the likelihood of an event occurring (the left hand side of the bow-tie) and the magnitude of the consequences of each risk event (the right hand side of the bow-tie).

By understanding these relationships, intervention and mitigation works are now better targeted towards activities that will have the greatest effect on reducing risk, minimising network delays, improving driver safety and saving money.

Assessing drainage on the railway

As with roads, drainage plays a crucial role in maintaining the performance of the rail network. If drainage is not functioning properly, water action can bring fines into the track ballast, causing settlement of the track and adversely affecting the stability of cuttings and embankment slopes.

Much of the UK's rail network pre-dates 1900 and includes large embankments and deep cuttings to provide the shallow gradients required for early trains. Network Rail is responsible for almost 190,000 earthwork assets, many of them built before the development of modern geotechnical design principles.

We developed Network Rail's first formal drainage asset management policy. This involved a consideration of the impact of drainage performance on the condition of the earthworks and track, with a truly cross-asset risk-based approach.

This means refurbishment of drainage that's in poor condition and causing instability of earthworks can be prioritised over other areas of drainage that might be in worse condition but causing fewer problems.

We also developed a decision-support tool to forecast capital and operational expenditure that would help Network Rail budget future maintenance and repair work on its earthworks, including improving the drainage asset.

The SCAnNeR (Strategic Cost Analysis for Network Rail) tool runs projections of the impact of repairs or rebuilding work over a 100-year period to determine the lowest whole-life cost options.

Whole-life cost considerations

With improved understanding of the role drainage plays in asset management, plus competing pressure to reduce costs and increase efficiency, consideration of whole-life cost is fundamental to asset management.

It's imperative that we continue to work with infrastructure owners to develop ever-more accurate ways of assessing assets to better target interventions and prioritise investment.

This will require better data gathering, management and modelling, pragmatic engineering and asset-specific knowledge to ensure the deterioration and degradation of assets is better understood.

"We have worked with infrastructure owners such as Highways England and Network Rail to help them develop methodologies for assessing drainage as part of their asset management strategies."

Opening opportunities with connected thinking.

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