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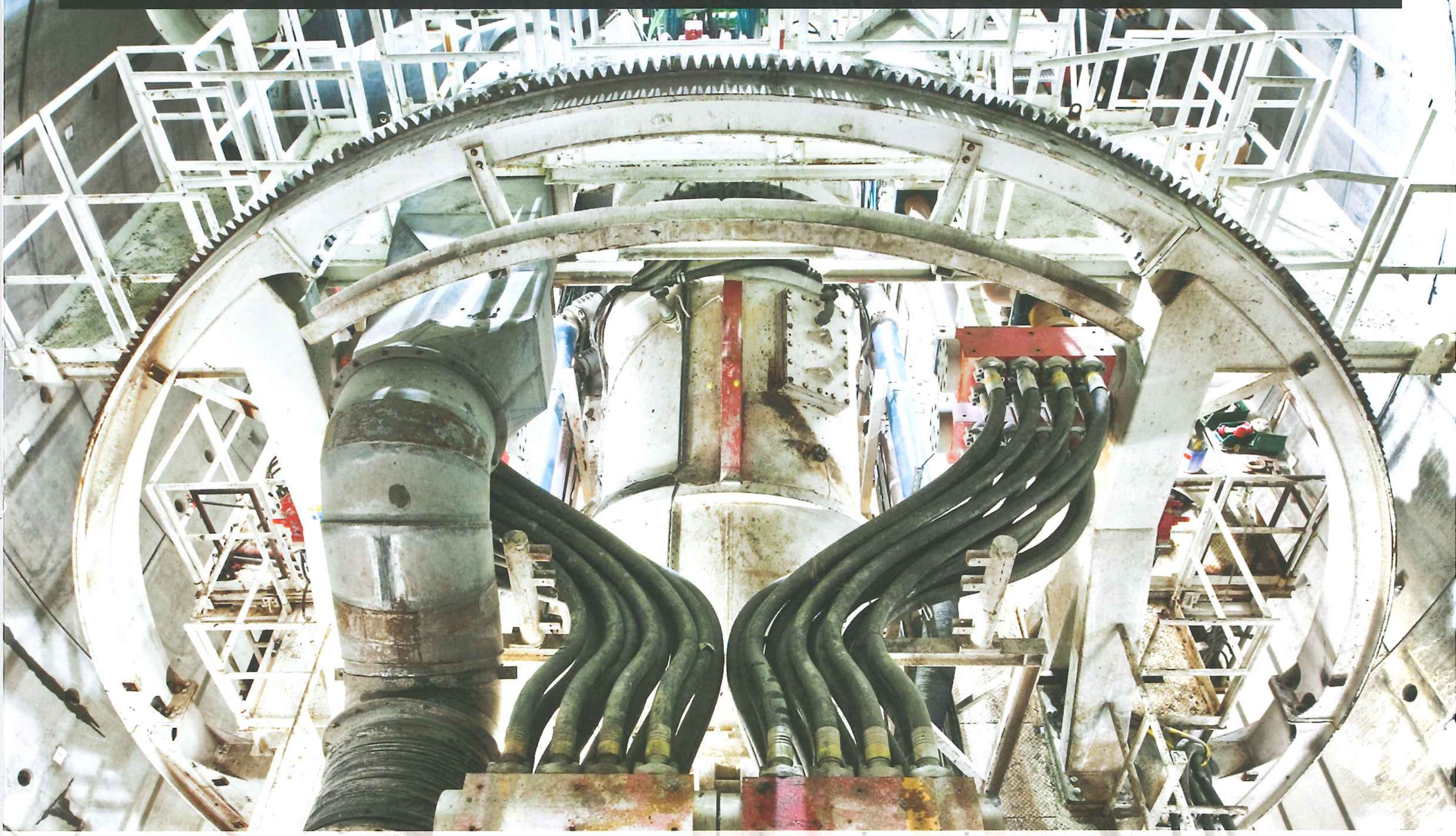

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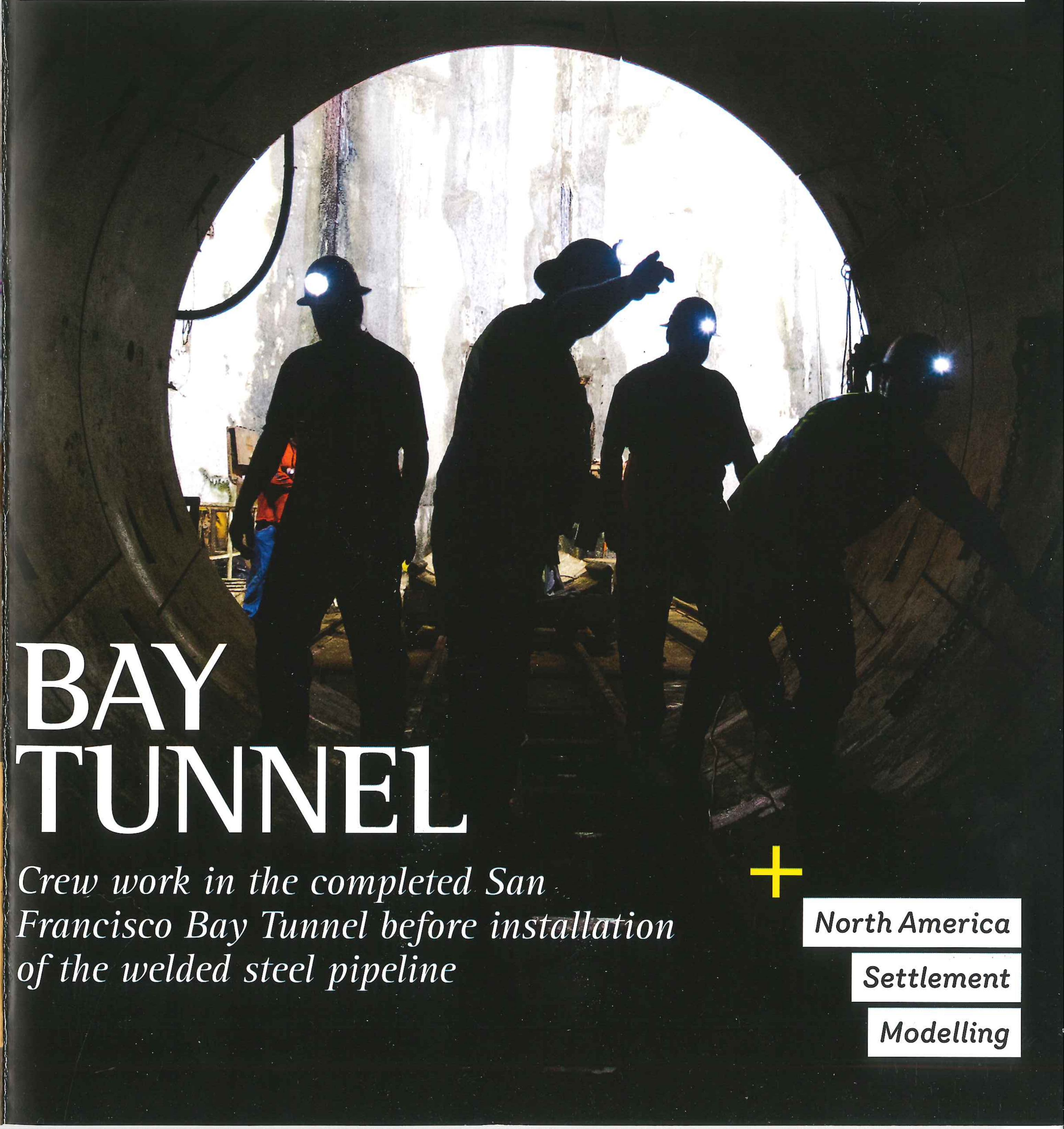
May 2015

Tunnels AND TUNNELLING



BAY TUNNEL

Crew work in the completed San Francisco Bay Tunnel before installation of the welded steel pipeline

\+ North America
Settlement
Modelling

LOFTY HOPES FOR WORLD'S HIGHEST

Alex Conacher
Editor

FAR ABOVE the destruction and loss of life caused by the Nepal earthquake last month, climbers sheltering at the Everest Base Camp endured days of avalanches. Huddling together under tables, and taking it in turns to dig one another out of smothered tents.

The mountain itself was at the epicentre of another tremour last month, as the global press grew giddy following an announcement by China's state-owned media that the world's highest mountain might soon be tunnelled as part of a link to Nepal. The proposed extension to the Qinghai-Tibet high-speed rail line would link Lhasa in Tibet with Kathmandu in Nepal would likely require such a tunnel.

The project would face extreme challenges, and the existing line is already a record breaker. The highest point of the 1,956km route is already at 5,072m above sea level. This is the highest railway in the world, rising over 200m higher than the Peruvian railway in the Andes. It also passes through the highest tunnel in the world (the Fenghuoshan Tunnel, 4,905m) and the longest plateau tunnel (the Kunlun Mountain Tunnel, 1,686m).

Political challenges have also been thrown at the scheme even at this early stage. India is reluctant for China to have more sway with neighbouring countries, while China claims that this project is being considered at Nepalese government's request.

And the United States government's policy of hemming in perceived Chinese expansionist ambitions has led Washington to declare the project a threat to regional security, the liberty of Tibet, and an environmental concern for the Himalayas.

These challenges aside, the growing excitement in the media apparently led an over-stimulated journalist to claim the tunnel would be complete by 2020, at which point Wang Menshu, chief engineer with the China Railway Tunnel Group decided to intervene, and give an interview to Chinese state media to douse the press with some reality.

Wang said that reported costs of CNY 100M (USD 16M) per kilometer were an underestimation of the complexity of the job, and contractors would not take the work. Fatal accidents on the existing line – on which over 100 workers died – were also a major concern to authorities. And at the heights required, there is also a need to provide oxygen for workers, which is an unusual logistical challenge.

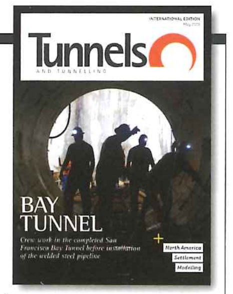
The length of tunnels required has not been revealed due to the early state of the studies, but they have been described as 'very long' due to the regions that political leaders want to connect.

However, despite the challenges, China has been considering this project for nearly a decade, and Wang concedes that if the political and financial backing were there, it would of course be possible. Just not by 2020

editor@tunnelsonline.info

What do you think? Send your views to the editor and join the debate

Cover
The font cover shows a miner of the Kargi hydel project as Lok Home of Robbins argues the case for TBMs



Next issue
In the next issue of Tunnels and Tunnelling we focus on North America in the World Tunnel Congrss issue. The tunnelling industry heads to Dubrovnik in a key event in the history of tunnelling. The ITA is being shaken up with a young members group.

This month...

20 YEARS AGO

This April saw the placement of the last of the tunnel segments by the Fionia TBM in Storebaelt's northern tunnel in Denmark. This momentous event brings to a close the tunnel boring portion of this project after almost five years. According to current time schedules, the first freight trains are expected to pass through the tunnel in the autumn of 1996, while passenger traffic is expected to commence at the beginning of 1997.
Tunnels and Tunnelling, May 1995, p.9

30 YEARS AGO

One of the most extraordinary international projects ever conceived could well become a reality following recent positive discussions about a fixed link between England and France, and now between Korea and Japan. At a 1981 Conference on the Unity of the Sciences, delegates from 100 nations agreed to a highway project stretching from London to Tokyo, involving a 200km tunnel link between Japan and South Korea. The proposed portal locations are at Fukuoka on the Japanese island of Kyushu to Kije-do in South Korea. Two islands between these points would act as access sites for the construction of the subsea tunnel breaking the link into three sections: a 60km-long tunnel from Tsushima Island to Koje-do, a 50km tunnel from Tsushima to Iki Island, and a bridge from Iki to Fukuoka.
Tunnels and Tunnelling, May 1985, p.8

Left: ***The Harbour Siphons project in New York, page 27***

News

North America

Technical

Insight

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Tribute

Contributors

MYLES O'REILLY
Myles is the outgoing chairman of the Tunnels and Tunnelling Editorial Advisory Board. Formerly he worked for the Transport & Road Research Laboratory in the UK. His famous 1982 paper on tunnelling induced settlements can be read on page 56.

BARRY NEW
Barry is another member of the Advisory Board, and is an associate of the Geotechnical Consulting Group, splitting his time between the UK and US. Barry writes a tribute to his colleague on page 55.

SR99 TBM rescued

USA — Contract Seattle Tunnel Partners (STP) completed the lifting process to remove the 57ft (17.4m) diameter cutterhead and main drive unit of the TBM mining the SR99 replacement tunnel on March 31, the Washington State Department of Transportation (WSDOT) announced.

The 2,000t section was lifted from an access shaft and placed on a repair platform nearby. Crews have since removed the machine's bearing block and, as Tunnels & Tunnelling goes to print, are expected to remove the main bearing. Manufacturer Hitachi Zosen will then begin making repairs. The lifts were performed using a Modular Lift Tower, supplied by Mammoet.

A new main bearing will be installed, along with repairs to the outer seal ring, among other work to create a more robust system. As well, steel plates are being added to the shield for reinforcement. After the TBM is reassembled in the access shaft, there will be a period of testing and commissioning before the TBM can relaunch.

The TBM stopped mining in December 2013, some 1,000ft from the launch shaft, with another 8,000ft left of the drive. Following hyperbaric inspections during early 2014, WSDOT and STP identified two contributing factors: a clogged cutterhead and high-temperature readings that led STP to discover damage to the seal system that protects main bearing. To make necessary repairs and replace the main bearing, STP chose to excavate an access shaft along the alignment rather than performing the work in the tunnel.

Crews completed excavation on the 83ft-wide circular shaft, 120ft (37m) deep on January 30, and then built a concrete cradle on the bottom to support the TBM upon reception. STP advanced the TBM in late February into the access pit for disassembly.

"The industry keeps moving forward with larger and larger tunnels," said Chris Dixon, STP's project manager. "The tunnelling industry is watching this project very closely so everybody is doing their part to make all of this happen as quickly and safely as possible, so that we can resume tunnelling as soon as possible."

STP comprises a joint venture between Dragados USA and Tutor Perini Corp. STP's team includes several firms local to Seattle, among them Frank Coluccio Construction and HNTB Corp. WSDOT awarded the contract in January 2011.

News briefs

CHINA

The 44.1km route has 30 stations. Running southeast from Linchang, the line crosses the River Yangtse in tunnel between Liuzhoudonglu and Shangyuanmen. All stations apart from one are underground. Construction started in January 2010 and was divided into northwestern and southern sections.

MEXICO

Soldiers have apprehended nine amateur tunnel engineers excavating an alleged drugs tunnel in Tijuana, Mexico. The eventual alignment would apparently stretch into California, USA. Some 150m had already been excavated. Following a tip-off, a spoil removal truck was also apprehended at the scene.

CHINA

Twelve workers that were trapped after a road tunnel collapsed in southwest China's Yunnan Province have been rescued, local authorities said at the end of last month. The incident occurred on 29 April in an operational road tunnel in Yunnan Province.

Underground freight solution to be trialled

GREAT BRITAIN — Mole Solutions is exploring the possibility of using small robot trains running on underground tracks to manage deliveries. It has reportedly received a funding packet from the British government to help test the viability of the proposal.

The UK-based company was formed in 2002 to focus specifically on underground and piped freight solutions. The system it favours uses magnetic wave propulsion; effectively mag-lev technology. In fact, the technology used here is simpler, cheaper and generates much less heat than maglev. It works with partners including DHL (3rd party logistics), Morgan Sindall (Tunnelling and Pipe construction), Laing O'Rourke (Civil Engineering), Force Engineering (capsule propulsion), WGH (capsule and track) and SoSustainable (socio – environmental), Local University for data gathering and analysis.

Mole Solutions said the small tunnels could be installed alongside existing transport infrastructure and create a system that runs 24 hours a day.

The steel carriages would run down concrete tubes measuring between 1.3 m (4.27ft) and 2.4m (7.87 ft), while the loading and unloading would also be handled automatically. Unloaded pallets would be stored in secure, temperature-controlled units at specified depot.

Capsules would not power themselves, instead electricity would be used to run linear induction motors (LIMs) built into the track. The magnetic fields would then propel the capsules to their destination. UK newspaper The Independent reports that the Department for the Environment, Food and Rural Affairs in Britain has stumped up cash for a trial run in Northampton.

There are benefits for supply companies like DHL or UPS, as they could get packages to customers more quickly for less cost. Despite the enthusiasm for the idea, all the parties involved admit there's a long way to go before we're picking up our deliveries from a Mole Solutions drop-off point.

The small-scale trial is designed to investigate the commercial, environmental and socio-economic impact of such a scheme before a decision is made on whether it can be rolled out elsewhere.

Shatin to Central Link TBM begins work

HONG KONG — The TBM ('Princess Wencheng') has begun work on Hong Kong's Shatin to Central Link. It launched from the To Kwa Wan Station site shaft to begin a 1.6km drive to Ho Man Tin Station – the Kowloon City Section of the project.

A second TBM, 'Princess Iron Fan', is set to begin her drive later this year.

BTSYM events calendar to take in new locations

GREAT BRITAIN — The British Tunnelling Society Young Members is expanding its programme of workshops and events to locations outside London. Starting with a presentation in May on recent experience with large diameter boring machines, then a workshop on contract management in June. Both are to be hosted in Birmingham.

Expect to see more as the group acts on its ambitions to spread its influence further afield, with a new drive for regional inclusion.

CBE announces Sao Paulo Metro mould contract

BRAZIL — CBE will supply 45 segment moulds to Consorcio Expresso Linha 6, the joint venture that will construct line 6 of the São Paulo subway system. Additionally, CBE will deliver a carousel setup for that the company says will "ensure segment production on site".

The precast segmental ring will have an inner diameter of 9,410mm and an external diameter of 10,210mm. Segments will have a thickness of 400mm and a width of 1,800mm. The concrete rings will be composed of six standard segments, two counter-key-segments and one key-stone.

The carousel facility comprises rails, concreting cabin, a four-line curing chamber, demoulding station and finishing line and will be designed at the head offices of CBE in France. The contract includes supply of sophisticated handling equipment such as four motor-operated storage clamps. After transport to Brazil, the carousel will be assembled by CBE technicians in cooperation with the technical staff of Consorcio Expresso Linha 6. The carrousel is able to produce 40 segments throughout an eight hour shift.

CBE Group already supplied segment moulds and precast facilities for the São Paulo metro line 5 which is currently under construction. The sixth line in São Paulo, has been scheduled to open in 2020. The new line with a total length of 15.3km and has 15 stations between Brasilândia and São Joaquim and is planned to transport 633 thousand passengers per day.

...and German rail project contract for the same

GERMANY — CBE announced its participation in the Rastatt Tunnel project that will form part of the high speed railway line between Karlsruhe and Basel. Some 42 segment moulds will be delivered to the German precast supplier Max Bögl, which is in charge of the production of approximately 15,000 concrete segments for the tunnel with a total length of 4.27km crossing beneath Rastatt from east to south.

The moulds have an outer diameter of 10,600 mm and an inner diameter of 9,600 mm. Each concrete ring will have a thickness of 500mm, a width of 1,950mm and 2,000mm and will be composed of four standard, two counter-key and one key segment. Segment production will be made in a static plant configuration.

The contractor is ARGE Tunnel Rastatt, a joint venture of Züblin and Hochtief. The building site has been prepared since November 2014, the assembly of the TBM will be in April 2015, tunnelling is scheduled to start in October 2015 and lining is planned to be finished in 2018.

Rome's B1 Metro Line handed over by contractor

ITALY — Salini Impregilo SpA completed and handed over to the city of Rome the last section of line B1 of the Rome Metro stretching from the Conca d'Oro station to the Jonio station.

The Jonio station, the new terminal, has a three-level covered car park with 250 parking spaces. The entire section comprises four stations, five shafts, 7,200m of 6.7m-diameter single tunnel track and 1,100 m of 9.8m-diameter double track tunnel.

Sunset Tunnel track replacement

USA — Last month the San Francisco Municipal Transportation Agency (SFMTA) began replacing the ageing track and other infrastructure inside the 1,290m Sunset Tunnel to improve safety and reliability of the N Judah rail service for Muni customers. The project will encompass track and infrastructure replacements inside the Sunset Tunnel, located between Cole Valley and Duboce Triangle, Transit Signal Priority (TSP) upgrades for nine intersections along the N Judah Line, and construction of two accessible platforms at Judah and 28th Avenue. Seismic upgrades involve structural retrofit of the tunnel portal retaining walls and their foundations.

Wendover proposes deep tunnel alternative

GREAT BRITAIN — Campaigners have launched a report arguing the case for an additional deep HS2 tunnel, which would better protect village of Wendover (population 7,000) in Buckinghamshire.

Under the current government plans, a deep bored tunnel will run only under south Buckinghamshire, with the line emerging near Great Missenden and a cut and cover structure running past Wendover.

However, a new study commissioned by Chiltern District Council and supported by Aylesbury Vale District Council, Buckinghamshire County Council and the Chilterns Conservation Board calls for a 24.2km tunnel throughout the whole of the Chilterns, emerging at Stoke Mandeville.

The report, produced by Peter Brett Associates, mitigates 'so far as is possible the impact on Wendover' and actually makes gives HS2 a 'more economic route to operate'.

The cost of this alternative route, dubbed the Chilterns Long Route, is estimated at GBP 1.85bn, making it GBP 400M more expensive than the current section.

It is also claimed that the tunnel meets new EU safety standards, with an underground fire fighting station taking the place of the previously required mandatory open-air gap on tunnels over 20km.

The Improve Life project to assess and improve air quality in metro stations and trains has been launched in Barcelona. The EU's LIFE programme is funding 50 per cent of the EUR 0.8M cost, and the results are to be made available to other operators so that the recommendations can be applied elsewhere.

Clear air project launched in Spain

SPAIN — The Improve Life project to assess and improve air quality in metro stations and trains has been launched in Barcelona. The EU's LIFE programme is funding 50 per cent of the EUR 0.8M cost, and the results are to be made available to other operators so that the recommendations can be applied elsewhere.

The Spanish Research Council for Scientific Research and metro operator TMB are to carry out a more thorough analysis following a study three years ago. The concentration of airborne suspended micro particles will be measured and their chemical composition analysed.

Measurements will be taken under normal conditions and during work that generates dust, such as track renovation. Specific components like rails, brake pads, ballast and electric wires will be analysed with a view to finding alternative materials for their composition or coatings to reduce dust generation. The effectiveness of tunnel ventilation will also be examined.

The first measuring apparatus has been installed

Indian Government mulls immersed tube tunnels

INDIA — The Indian Government may commission two immersed tunnels in the next few years. The shipping ministry has envisaged these projects – one between Kakdwip and Sagar island in West Bengal, and the other connecting Chatham and Bamboo Flat in Andaman Nicobar islands.

The Times of India reports that shipping minister Nitin Gadkari said recently his ministry is exploring the possibility of building these immersed corridors to improve connectivity, and that the task has been given to National Highways and the state-owned Infrastructure Development Corporation Ltd (NHIDCL). NHIDCL has called tenders from consultants to prepare the techno-economic study of both the stretches.

"We have given two options to the bidders – to prepare reports for building elevated stretches and immersed tunnel. The ministry will take a decision based on their technical feasibility and the amount required to build these infrastructures," a senior NHIDCL official said.

As per the bid document, the consultant has to carry out detailed study for constructing the corridor for both rail and road traffic in the case of Kakdwip and Sagar Island connectivity through Muri Ganga River. This will be around 3.5km. "The connectivity will prove beneficial for cargo movement with the mainland. There will be more demand once the Sagar Port project starts," a shipping ministry official said.

He added that as per their rough estimate submersible tunnel will cost less than the elevated track on this stretch. "Immersed tunnels are aesthetic and these pose no hindrance to the movement of ships," said the official.

The other proposed corridor between Chatham and Bamboo Flat in Andaman Nicobar Islands is about 2km. At present, people need to travel about 48km to reach from one point to other through land. The construction of an immersed tunnel or elevated corridor will bring the two regions closer.

The ministry alleged that immersed technology had not been used in India thus far.

Young tunnel engineers at forefront of achievement awards

GREAT BRITAIN — Two past chairs of the British Tunnelling Society Young Members (BTSYM) have been shortlisted for the Asian Women of Achievement Awards. Joanne Sui and Anita Wu, both of London Bridge Associates have been nominated for the awards, which were launched over 15 years ago to celebrate the achievements of successful Asian women in British society.

Asked if this represented a growing recognition of the tunnelling industry, Wu agreed, adding: "It also shows the growing number of women in engineering, and that engineering is being correctly recognised by others as an admirable profession."

Sui said: "These awards are targeted at those in a diverse range of industries including business, entrepreneurship and engineering. I hope that people look at our achievements and see that tunnelling is an important industry that is not just a 'man's world'."

And for aspiring tunnel engineers, Sui recommends: "Get as much experience as you can, it's amazing what you can learn from other people. Join [a Young Members' group] and meet new people, there are so many likeminded people in the industry. Always remember that there is plenty more to learn.

Wu added: "Always ask questions and work hard. If you have to put in an extra 20 per cent of effort compared to others to understand something then do put in the extra 20 per cent. Do not be afraid of challenges, see it as an opportunity and grab every opportunity you can."

David Sharrocks, MD of London Bridge Associates commented: "It is to both of their great credit that they have been shortlisted by AWA as high achievers. They do far more than their day job.

"The fact that they are young Asian women is both important and unimportant. It is important because they do help to encourage other youngsters, other Asians and other women by being visible and by their actions and initiatives.

"Ultimately the wider the pool of talent that the tunnelling industry can draw upon the better the industry will perform.

"It is also unimportant because it is the combination of their personalities, skills, knowledge and experience that enables them to do their jobs as tunnelling engineers on Tideway and the Bond Street Station Upgrade."

Anita Wu (left) and Joanne Sui both work for London Bridge Associates in London, UK

Herrenknecht pipe installation system's third success

SWEDEN — Herrenknecht's newly developed semi-trenchless method for pipeline installation has completed its third successful mission. South of Stockholm, using Pipe Express Züblin Scandinavia AB installed a water pipeline more than a kilometer in length within twelve days. Groundwater lowering was not required despite a water level just below the terrain's surface. In the most productive 12-hour shift, 221 meters of pipeline disappeared into the ground; the average construction performance was 0.70 meters per minute. About 60 percent of the construction time was taken up just with welding and coating the up to 224m long steel pipe strings.

A spokesman said, "We see strong potential for the new method on the market."

TBM ready to begin excavation in Laos

Xe-Pian X-Namnoy TBM starts work

LAOS — March saw the start of TBM tunnelling works on the 11.8km-long, low-pressure headrace tunnel for the Xe-Pian Xe-Namnoy Hydropower Project.

A ceremony was arranged and attended by officials from Xe-Pian Xe-Namnoy Power Company, SK Engineering & Construction, Seli Overseas and TBM manufacturer Terratec.

The TBM had begun to advance through a 500m of tunnel adit excavated by drill and blast as T&T went to press. Once the TBM reaches the tunnel face, it will commence work on the main 11.3km bore.

The machine is a 5.74m diameter double shield hard rock TBM designed and manufactured by Terratec. It will have to excavate through two main geological formations, the Tholam Formation consisting of mudstones and siltstones and the Champa Formation including siltstones, sandstones and conglomerates.

The TBM was tested and accepted at the factory in December. Since then, it was dismantled, transported to site and re-assembled within approximately three months, which according to the manufacturer was logistically challenging due to the remote location of the site.

The project also calls for the construction of two central cored rock fill dams, waterway tunnels with a vertical shaft and a powerhouse generating capacity at 410MW

Third District of Columbia TBM ready to launch

USA — DC Water hosted a ceremony on April 14 to name and christen the third TBM in its fleet, which will mine the First Street Tunnel, part of the 13.1-mile long Anacostia River Tunnel system.

The 2,700ft (823m)-long tunnel is 80ft-160ft (24m-48.8m) below ground and will excavate through frozen ground. A contractor JV of Skanska/Jay Dee secured the USD 157M design-build contract in October 2013.

District of Columbia Mayor Muriel Bowser said, "This part of DC Waters Clean Rivers Project will bring relief to these neighborhoods that have experienced flooding for more than 100 years. The First Street Tunnel is the product of extensive collaboration between DC Water and the District agencies to find an innovative and timely solution to damaging local flooding. The project will bring needed relief to the community and help put residents on a pathway to the middle class."

Jacobs wins early design work for Heathrow rail link proposal

GREAT BRITAIN — Jacobs Engineering has been tasked with design and studies work for a proposed Network Rail link to Heathrow. The 'Western Rail Access to Heathrow' project will apply for a Development Consent Order in early 2016. Jacobs will produce the design for the proposal documentation. The scope of work includes topographical surveys and geotechnical investigations, tunneling design for the new 3.1-mile (5km) route, and railway systems designs for track and overhead line equipment.

The proposed Western Rail Access to Heathrow includes a new direct, double track link between the Great Western main line at Langley in Berkshire (16 miles west of Paddington Station in London) into Terminal 5 at Heathrow airport.

The link is expected to provide greater connectivity from south Wales, the west of England and the Thames Valley; making journeys faster, reducing congestion on other routes, and providing significant economic benefits for businesses in the region. The project also aims to reduce CO_2 emissions by the equivalent of a million road passenger trips to and from Heathrow.

Jacobs Group Vice President Bob Duff stated, "Jacobs is delighted to continue to leverage our global rail experience on this planned project.

We look forward to contributing tangible solutions to support Network Rail's emphasis on sustainable design at the heart of the new rail link."

Jacobs delivered pre-feasibility and feasibility studies in the early planning stage of the project which identified significant potential cost savings. Currently in public consultation, if the Western Rail Access plans are approved, it is expected that the new service would be in operation by 2021.

Crossrail breaks initial apprenticeships target

GREAT BRITAIN — Crossrail has shot past its target of taking on 400 apprrentices after training some 8,000 workers at its east London tunnelling academy. The East London Advertiser reports that some 446 apprentices had been trained from scratch as of 1 April.

Speaking earlier this year, Crossrail's 400th apprentice Fatima Alghali said: "I can't recommend apprenticeships more highly. Working on Europe's largest construction project has given me an unforgettable introduction. No two days are the same, and not only am I learning from some of the best engineers in the industry I will end up with a qualification that will give me a great start to a career. It's also a huge help that you earn a salary as I'll be debt free when I qualify."

Terry Morgan, Crossrail Chairman said: "In 2009 Crossrail made a commitment to reinvigorate the UK's tunnelling and construction skills base with new talent. I'm delighted that we have achieved this major milestone but we will not stop there, and will continue to create new apprenticeships as the project evolves. As a former apprentice I have seen first hand how beneficial apprenticeships are for both individuals and employers. Crossrail's approach to skills training is a model that can be adopted across the industry to help deliver the UK infrastructure projects of the future."

Crossrail committed to delivering at least 400 apprenticeships over the lifetime of the project. Around two in five (44 per cent) Crossrail apprenticeships have been filled by people that were previously not in work; a figure that's double the UK average. They have been trained in a range of professions from construction to accountancy, quantity surveying to business administration.

More than 40,000 people now start an apprenticeship every year in London. Boosting youth employment is a key priority for the Mayor and apprenticeships are one important way to achieve this. Since April 2009,

Transport for London and their suppliers have created over 5,000 apprenticeship roles. While many of the apprentices are in London, a number are employed across the UK as a direct result of TfL contracts with other businesses.

Atlas Copco invests in training facilities for staff

SWEDEN — Atlas Copco Construction and Mining service divisions have invested in a range of new training facilities. These include state of the art training simulators, industry-leading activity based offices and investment in workshops.

A spokesman said, "In the mining and construction industries, equipment owners continuously seek to increase productivity from their machines and are now looking to manufacturers to provide operator and service training to increase performance."

Atlas Copco's Business Line Manager for Construction Service, comments: "With our newly refurbished workshops we are able to carry out all kinds of service work from overhauling heavy hydraulic breakers to servicing large compressors and generators. We hold workshops for dealers and customers to train their service technicians on how to maintain our equipment. These sessions teach them about our products and more importantly how to service and maintain them.

"It's also a good opportunity for us to learn how we can help our customers to get the most from our machines."

Atlas Copco's Mining Service Division offers various driller training programmes. The training for drill rig operators takes place on a drill rig simulator. This means that any mistakes the operator makes whilst training will have no real-world consequences and drillers can be trained up to a high standard in a short space of time, all before they work on a real-life drill rig.

The new training facilities have been used to hold training sessions for staff, dealers and customers. The increased focus on training has been complemented by the new Activity Based Working (ABW) style that allows staff to collaborate, have meetings and work in quiet zones depending on what work they're doing.

Atlas Copco have service locations throughout the UK and Ireland including Hemel Hempstead in England, Stirling in Scotland and Portloaise in the Republic of Ireland. Their service network includes a network of 25 field based service engineers located across the UK and Ireland.

Holborn underground fire not deliberate, firefighters say

GREAT BRITAIN — A fire that caused billows of smoke and the closing of Kingsway in London last month was not started deliberately, firefighters have said.

An electrical fault damaged an 8in (200mm) gas main, which ruptured and fuelled the fire.

It lasted several days. Kingsway remained closed as Tunnels and Tunnelling went to press, and restrictions were in place in surrounding roads today as work continued to complete repairs.

A robot normally used by police to investigate suspect bombs, and heat-seeking cameras on a helicopter were used to help put out the Holborn fire.

The London Fire Brigade outlined the extent of the challenge it faced in dealing with the blaze, as the initial findings from an investigation confirmed it was sparked by an electrical fault in service tunnels under Kingsway. The brigade said there was "no sign of deliberate fire-setting".

Infra-red images from the police helicopter provided "invaluable information" for firefighters on the ground. The robot was sent into the tunnels to provide information to help them plan how to gain access once the area was safe.

London fire commissioner Ron Dobson said: "We discussed a number of plans which included using high expansion foam but as there was no compartmentation in the tunnels there was no way of knowing where the foam would go and what structural damage it may have caused.

"As the gas leak was fuelling the fire it was much safer to contain it while the escaping gas was burning off. If the fire had been put out before it was isolated it could have resulted in a build up of gas over a wide area leading to possible explosions. An example is your gas hob at home, turn the gas on and light the ring and it is perfectly safe as long as you monitor it, but put the fire out and leave the gas running and it could result in your house exploding."

Dobson said the incident had demonstrated the challenging nature of some fires in older cities. "This technically difficult fire shows just how complex London can be and how unseen risks underground are significant."

It had been suggested by media that a recent large-scale jewellery heist opposite the Tunnels and Tunnelling offices near the Kingsway site might be linked to the fire, but this has been rejected by officials.

Funding packet announced for Melbourne Metro...

AUSTRALIA — The Labor Government has announced AUD 1.5bn (USD 1.19bn) to cover all anticipated planning, design and significant early works ahead of major construction of the Melbourne Metro Rail Project in 2018.

The huge funding injection provided in the 2015-16 Victorian Budget will allow the Melbourne Metro Rail Authority to complete the reference design, undertake the statutory planning process and get this public transport mega-project started.

The funding also provides for land acquisition, preparation of Expression of Interest and Request for Tender documents, and significant early works such as tram rerouting and service relocations, ahead of contract award and major construction of the tunnels.

Premier Daniel Andrews and Minister for Public Transport, Jacinta Allan, made the announcement today at the project's first geotechnical testing site since the project was abandoned by the previous Liberal government. Geotechnical investigations are a key part of planning and designing the project, providing critical data about ground conditions and soil quality. The information gathered will inform the precise alignment, depth and design of the new rail tunnels and underground stations.

Over the coming months 140 boreholes will be drilled between South Kensington and South Yarra. This testing builds on previous geotechnical work undertaken for Melbourne Metro Rail, and will be complemented by site surveying, underground service identification and other preparatory works.

A government spokesman said: "The Melbourne Metro Rail Project will transform the region's rail network into an international style metro system, like London or New York. It will increase the capacity, reliability and efficiency of Melbourne's busiest train lines, allowing 20,000 more passengers to use the train system in peak hour.

Premier of Victoria, Daniel Andrews said, "The AUD 1.5bn (USD 1.19bn) announced today allows us to design, plan and complete significant early works on Melbourne Metro Rail. Melbourne Metro Rail is the biggest public transport infrastructure project in Australia, and the biggest overhaul of our public transport system since the City Loop."

...as the East West Link is cancelled in a political argument

AUSTRALIA — The Australasian Tunnelling Society (ATS) has published an explanation to the current funding situation in Victoria: The Victoria state government has announced a deal to formally end the controversial AUD 10.7bn (USD 8.47bn) East West project. This has sparked a furious response from the federal government, which had committed to AUD 3bn in funding.

A statement issued by prime minister Tony Abbott said "the Commonwealth Government is dismayed by Victoria's decision not to proceed with building the East West Link", saying that it "sets a dangerous precedent for future projects and threatens further investment in much-needed infrastructure in our country".

"AUD 3bn from the Commonwealth Government remains on the table for any Victorian Government which wants to build the East West Link", the statement said. "We will talk to the Victorian Government about other projects, but the truth is there is no other major shovel ready project in Victoria."

Victorian premier Daniel Andrews and treasurer Tim Pallas said a Heads of Agreement had been signed which will see the projects assets transferred to the state, without any compensation to the companies in the construction consortium. AUD 339M covering the bid process, design and pre-construction activities will not be retrieved.

However, a report in the Financial Review said "the total cost the government of the abandoned project stands at more than AUD 900M".

AUD 81M of fees were incurred to establish the Project Co credit facility of AUD 3bn. Andrews said the state intends to negotiate with the banks to take over that facility to contribute to funding for the proposed Melbourne Metro Rail Project.

In February, the Melbourne Metro Rail Authority was established by the new government. Since then it has conducted planning and technical work to determine the most appropriate route and depth for 9km twin tunnels running under Melbourne's CBD.

The day after the East West Link announcement, the Victoria minister for transport Jacinta Allan said the investigations had determined that a route under Swanston Street was the most cost-effective option. A key challenge is how the new tunnels will interact with the existing City Loop.

The planning work has determined that "building the tunnel above the City Loop at a depth of around 10m – instead of below the City Loop at more than 40m – is the best option for commuters".

Other factors include safety in the event of an emergency and efficiency in construction. With the preferred route identified, more detailed investigations will now be conducted.

Safety concerns over Hai Van Pass Tunnel Upgrade proposal

VIETNAM — A project to expand the Hai Van Tunnel's emergency lane into a main tunnel has drawn safety concerns. Le Van Trung, director of the Da Nang City Department of Transport, said he supports a project to build another tunnel through the Hai Van Pass to cope with the increasing traffic volume, but is concerned by the implications of the loss of a safety tunnel.

According to local media, investors had already dismissed this option as too costly. And Nguyen Dinh Bach, general director of Hai Van Tunnel Management and Operation Corporation disagreed with safety concerns, saying that even after the emergency lane is turned into another main tunnel, there would be 'no hindrance' to rescue activity as the current main tunnel and the new one would still be connected by cross passages after the upgrade.

The existing tunnel opened in 2005. The single bore runs 6.3km at 12m in diameter but has a safety and maintenance tunnel alongside it connected by 15 cross passages.

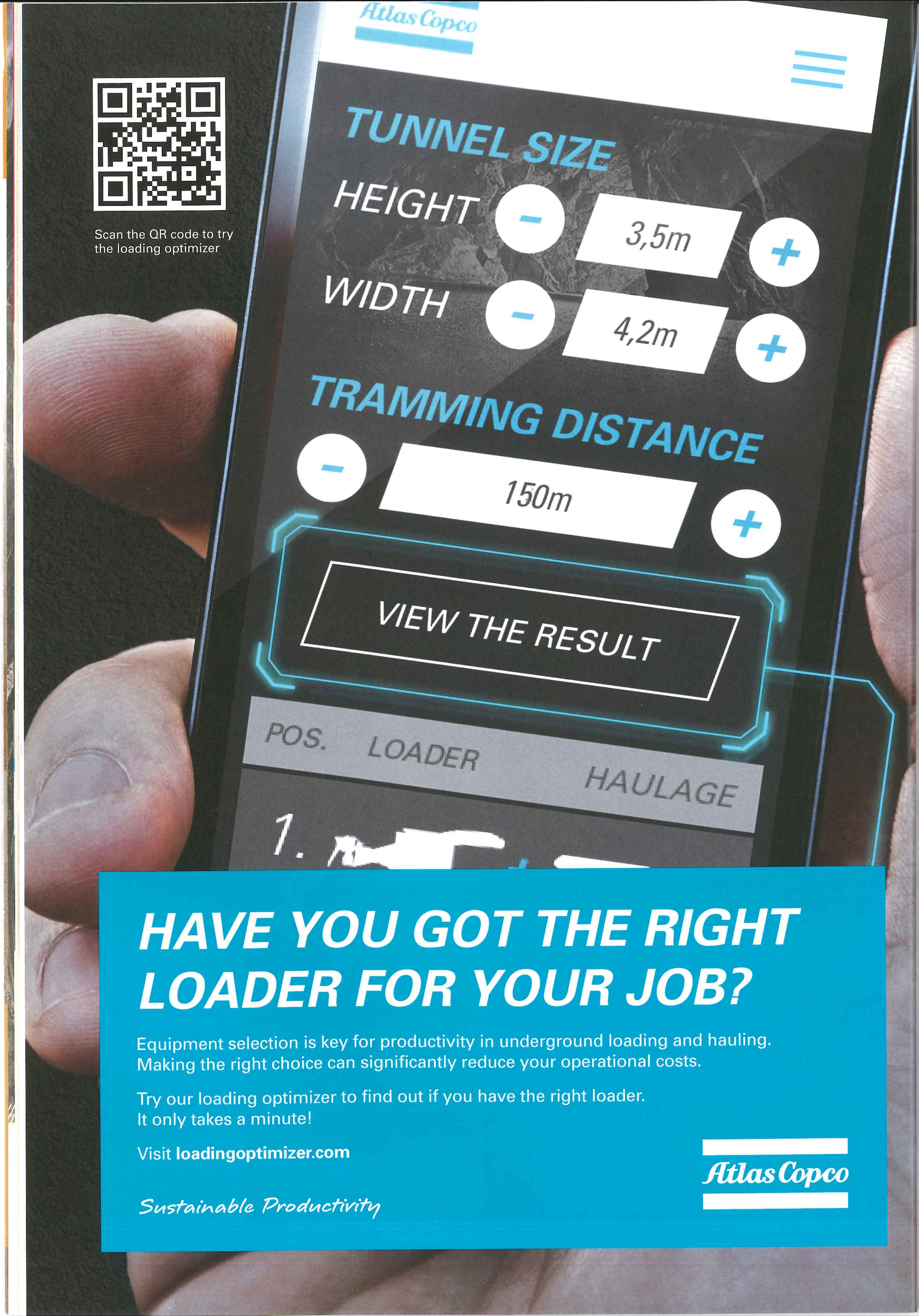
It was constructed by a joint venture of Japan's Hazama Corporation and Cienco 6 of Vietnam.

If approved, the project should kick off in January next year and finish in the first quarter of 2019. It is expected to cost USD 300M.

What do you think? Send your views to the editor and join the debate

editor@tunnelsonline.info

Left: Over the weekend of April 17-20, in the early morning hours, Crosstown Transit Constructors, a joint venture of Obayashi Canada, Kenny Construction, Kenaidan Contracting and Technicore Underground, extracted the two TBMs that have been tunnelling the western segment of Toronto's Crosstown's underground section, from a shaft located just west of Allen Road.



SAN FRANCISCO SUCCESS

The first water passed through the 8km-long San Francisco Bay Tunnel in October 2014, well ahead of an original 2015 schedule. The project also came in well under budget, **Adrian Greeman**

Adrian Greeman
Is a former editor of and long-standing regular contributor to *Tunnels and Tunnelling*

PROJECT MANAGER Ed Whitman can be forgiven some slight boasting about the contractor's team on the new Bay tunnel crossing, declaring that "we had the right amount of planning and set ourselves up for a fast production level extremely well." The project is after all several months ahead on completion time and with a final cost of USD 288M also less expensive than its estimated USD 313M.

Whitman is half-joking and only makes these restrained comments later in an interview in response to a fair question. As well as credit for the joint venture of Michels/Jay Dee/Coluccio, he says a good design by consultant Jacobs Engineering, and project collaboration with the client San Francisco Public Utilities Commission (SFPUC) all helped the work go well.

But he is also entitled to plaudits for a relatively difficult tunnel that faced mixed soft and hard ground with potential hazardous materials like asbestos, strong environmental challenges above ground, seismic complications, and logistic constraints working from one end only of a 5-mile (8km) long bore, 15ft (4.6m) in diameter (see *T&TI* June 2011). Added difficulties included installation of a steel pipeline within the tunnel, embedded in a seismic resistant cellular concrete internal lining.

The project is a component element of a USD 4.6bn Water System Improvement Project designed in part to ensure earthquake resistance to water supplies in the San Mateo peninsula, the central part of San Francisco to the south of the Golden Gate Bridge, where there is a 2.5 million population. It repairs and replaces old pipelines across the bay originally installed for similar reasons after the devastating 1906 earthquake, upgrading the so-called Hetch Hetchy system to modern seismic standards.

The tunnel component is the first bore ever made underneath the Bay – the old pipes sit on the bed – and so the geology was a relative unknown. Test drill probes indicated mostly clay but with embedded sand lenses up to 2ft thick (0.6m) and there was an outcrop of the San Francisco complex, harder ground up to 1,400 psi in strength (10MPa), running for some 800ft (250m).

"We also had an unknown area underneath the Salt Pans," Whitman says. These are areas in the shallows of the Bay edges, divided into evaporation basins for the extraction of mineral salts of all kinds, used for industrial purposes. It is an industry present over the last century or so and one of the largest such in the world. The pans are divided by berms built on relatively soft Bay mud and the owners feared the impact of heavy drilling equipment could create instabilities. "They hold back a lot of brine," he says.

In the event the ground 120ft (36.6m) underneath proved to be a similar clay to the rest, as expected.

First of the key decisions was choice of a tunnelling machine to cope with these clays, wet sands and the Franciscan complex, known to be harder but which is very heterogeneous with metamorphic components and even volcanic basalts and therefore capable of delivering surprises.

The choice was an EPB TBM made by Japan's Hitachi-Zosen, with a cutterhead designed primarily for the soft ground but fitted additionally with shell bits for harder rock.

"They are like rippers but with a concave shape like a seashell," Whitman explains. "We went for Star Alloy cutters which are harder and they performed by well. We had a few interventions but saw no need for replacements and in fact went through the rock zone with almost no wear on the cutterhead."

Guidance was done with a Japanese Enzon system, recommended by Hitachi, which uses a system of robotic total station and TBM mounted prisms to track the machine in relation to fixed prisms further back along the tunnel line. It also pulls data from the machine systems he says to give actual and planned locations.

He says the entire TBM setup went very well and he is pleased with the machine performance overall declaring it to be, "well built and one of the best machines I have worked on."

Challenges along the way included getting used to the clay which was

288
Million dollars is the final cost of the tunnel, and under budget

5
The tunnel's length in miles, which had only one end from which to work

***Opposite:** Moving one of the 40ft-long pipe spools*

***Below:** The TBM operator speaks with project staff*

unexpectedly stiff, so much so it could not be broken with shovels in the starter pit excavation and tended at first to emerge from the pressure chamber screw conveyors as "one long log".

Some juggling with conditioning was needed as both polymers and bentonite made no difference.

In the end the team found a stabilised grout, being mixed for the injection behind the segments, worked quite well. It was a cement, water, bentonite mixture with stabilising additives which kept the mix "live" for almost a month. The next problem however was tackling the sand lenses. Unlike the impermeable and dry clay the spoil was full of water and tended to emerge as a "slop".

Above: ***A crew member inspects the TBM***

Whitman says, "The difficulty was to change the conditioning in time because the operator would hit a lens and fill the chamber before he knew it."

"The sand 'slop' disrupted the balancing air bubble in the chamber and then if it built up to the extraction screw air would travel at some velocity and splatter everything," he adds.

The problem was partly due to the choice of twin extraction screws which were designed with an open spiral rather than one around a spine shaft. The shape gives a higher capacity, which the contractor wanted for speed of operation but has less friction to resist such surges.

The trick was judicious use of calliper gates mounted between the two screws which are set one behind the other, and a guillotine gate at the end.

Further spoil problems were faced in the harder ground which tended to come out in long slivers that could jam the open screw configuration. Slowing the drive rate helped deal with that.

Another challenge was to balance the forward pressure of the machine for speed with requirements of grouting at the back. As on many smaller tunnels, the six segment universal ring was grouted through the segments, using the cast in lifting holes.

"Too much pressure could squeeze material along the shield into the annulus," Whitman says, "so you had to juggle that." Grout was injected into the ring as it emerged from the machine, with sodium silicate admixture to undo the stabiliser effect and set it.

Segments were from a factory in Stockton, just a 90-minute truck drive away. They were produced by subcontractor Traylor Shea who conveniently had just completed a tunnel project in Sacramento and had spare precast capacity. Steel moulds came from France. The segments used a steel fibre reinforcement which was fine, says Whitman, "though it leaves the segments slightly more prone to breakage – they are not made of glass of course, but cracks propagate in a way they don't with a cage. We had to be careful handling them."

There were a few broken units, but not many and only one ring had to be re-done, he says. On site they were lowered into the shaft by a gantry crane, a specially fast unit custom built for the project by American Cranes "at some expense," says Whitman ruefully. From the bottom they were delivered to the machine by a rail system.

As with all the decisions on the project Michels/Jay Dee/Coluccio had this designed with an eye to production speed, and it could carry two full rings at a time, with the TBM back-up train able unload and store them.

"That way the machine would not find itself waiting for rings," Whitman says, "even at the end of the drive when the single track haul train was making a full 8km trip and back to the starter shaft."

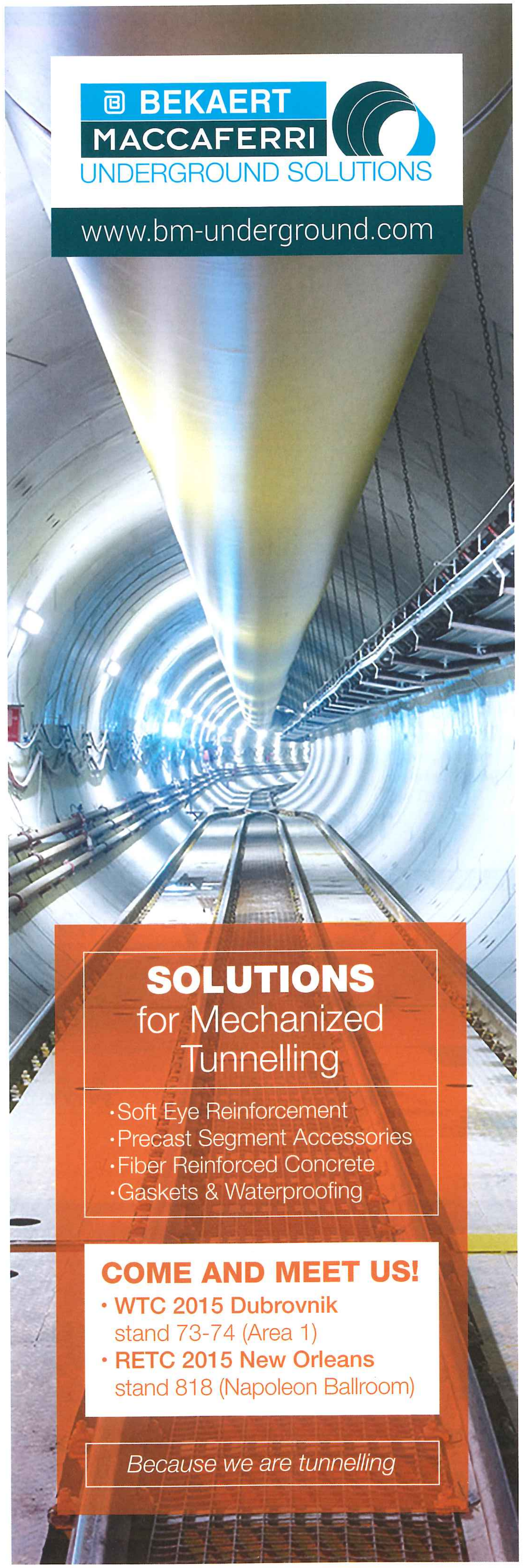
The train used electric locomotives, also Japanese, which Whitman says proved just right, the batteries lasting long enough to last through an entire 10-hour shift before recharging was needed. Spoil removal meanwhile was done with a conveyor, leaving the tracks clear for deliveries. Inside the tunnel this was a Goodyear system, brought in from a previous location. It ran up the side of the shaft side to a motor at the top. But the spoil was tripped off the belt at the shaft base to be picked up be a vertical belt. This was carefully thought out too. "We looked at various systems including a sloped cutting or tunnel out of the shaft but decided to use a vertical conveyor. But the usual bucket type could have been a problem, because of the sticky nature of the spoil."

The team used a relatively new "box" design from Japanese maker Hirosawa, which has "accordion style" pleated sides that can grip the spoil for the lift and then more easily discharge it at the top. From there it ran another 500ft (130m) to a spoil handling pit again on a Goodyear line, with mobile placer conveyors to distribute it around a large "bean-shaped" pit.

"Too much pressure could **squeeze material along the shield** into the annulus, you have to juggle that."

"We used a big area because the final disposal sites were at the edge of the bay on marshy ground, and they could have problems in bad weather," he says, having to shut for perhaps some days so there had to be room to stockpile.

The tips are part of a major environmental reclamation around the Bay, which is restoring some of the old salt pan areas to the condition thought to represent the original natural state. It will all make up part of the Don Edwards wildlife refuge, first of its kind in California. Just under 300 species of



birds are likely to use it. The big spoil area came in useful for the harder ground spoil. It had been anticipated that this could be contaminated with natural asbestos, requiring segregation, and disposal to special sites. In the event there was less than expected.

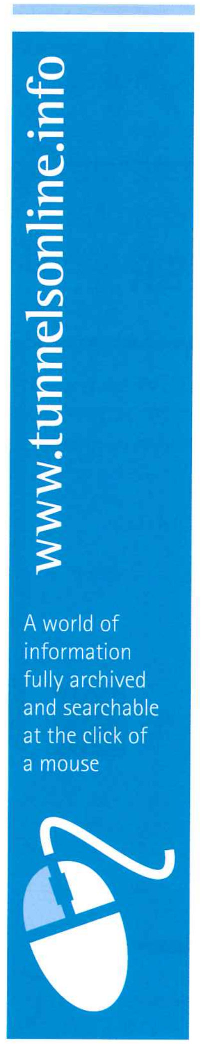
"But instead we found naturally occurring heavy metals like chromium, cobalt, an caesium," Whitman says, "and we had to treat the spoil separately for that reason." It took 24 hours to test each batch from a 100ft (35m) of drive to see if it was safe or not. While the tunnelling was underway the contractor was also figuring out the end point shaft excavation. The start shaft, made back in 2010 when the work began, had been difficult enough. It used diaphragm (slurry) walls and excavation inside under water to the 120ft (36m) tunnel depth, and required divers to complete.

"At that depth they can only work for 40 minutes before going through decompression, and then waiting for a 24-hour period for the next job," Whitman says.

The 27ft (8.3m) wide end shaft had constraints on its location. On one side it was close to the environmentally protected area and the designer, fearful of potential spillages, wanted to keep it as far away as possible. But the other side was close to the old pipeline, running on trestles and in a sensitive condition. The contractor felt a redesign was possible, allowing a reduction in size to 20ft (6.1m), sufficient to take out the core part of the TBM if the shield was made sacrificial and left in the ground. That gave a bit of space but even so the heavy loads of diaphragm wall rigs were thought too much, as would be a caisson.

"We opted for ground freezing instead using a brine system," Whitman says. The hardened ground was carved out with a roadheader in 5ft increments lined with ribs and lagging before a permanent concrete wall.

The shaft was then used to remove the main parts of the TBM, which finished its drive in January 2014, six months ahead of schedule, having averaged 34ft (10.5m) a day and peaking at 220ft (67.7m). From both ends, the tunnel had to be cleared not just of the long TBM train but also of rails, conveyor and so forth, to make way for the second phase of the job, installation of the pipeline. The water line is an embedded pipe sealed within a concrete jacket that protects against expected seismic shock in this most vulnerable of areas. It also gives corrosion protection, particularly by using a PFA rich mixture for the concrete design, explains Jacobs Engineering construction manager Robert Mues.



Below: ***Completed tunnel before installing the welded steel pipeline***

The alignment deliberately does not cross the two major faults along the Bay but is close to them and future shocks.

Installing the pipeline has also been complex. First the 9ft (2.8m) diameter pipe has to be assembled within the tunnel from the 40ft-long spiral welded sections delivered. It then has to be welded into a single string, and finally embedded by filling the 18in (460mm) annulus with concrete.

This can be difficult enough above ground where at least the joining operation can be done from the outside, obviously not possible in a tunnel.

"The challenge is that pipes that length behave like wet Chinese noodles," Whitman says. To keep each length stiff and properly positioned for welding a special "pipe placer" unit is used, "like a long travelling beam a bit bigger than a pipe length."

These are used commonly though the JV had its own tailor made version built, and in fact modified after a few initial runs highlighted some flaws in its operation. The unit has to travel through the pipe, and then pick up the next delivered string from the tunnel floor and hold it in position for welding. This is not easy as high precision is required firstly and secondly, the roundness of the pipe has to be exact.

"The pipes tend to go out of shape and so there is a pipe rounder, looking rather like a TBM gripper but all around the inside of the pipe." Whitman says. "This holds the pipe shape against a backer plate slid over the joint against which the welders can then join the two sections."

But this work is fraught too. "You can easily get a 'wave' in the pipe steel, running ahead of the weld which causes problems as you finish," he explains. The possible distortion can also arise from temperature differences expanding the steel as it is welded. "So first you have to stitch the weld to hold it."

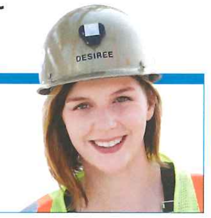
Once all this is done the pipe have to be carefully positioned inside the tunnel, supported on stools at intervals with screw jack adjusters to make sure it is centrally placed. Stiffeners inside the pipe are positioned exactly against the outside stools to prevent loads buckling the pipe.

"Then you backfill the entire length in one go," Mues says, "which is also problematical because of buoyancy effects as the grout travels along the annulus."

A series of grout fillings lifts were used to minimise the effects and the pipe was finally completed in the autumn last year

HARBOUR RESCUE

At a harbour-side jobsite in New York, USA crews are smoothly wrapping up a successful water tunnel project. The journey to TBM breakthrough in January 2015, however, was anything but smooth. Robbins technical writer **Desiree Willis** reports



Desiree Willis
Desiree has covered a range of topics for *Tunnels*, as Robbins' technical writer

IN OCTOBER 2012, New York's Harbour Siphons Project and its 3.8m (12.5ft) CAT EPB ground to a halt when hit by Superstorm Sandy. Despite contractor Tully/OHL JV's best efforts to mitigate anticipated flood risks, the launch shaft was inundated with seawater, flooding the tunnel and TBM just 460m (1,500ft) into the 2.9km (1.8mi) long drive. A team of Robbins and OHL personnel were able to document, reverse engineer, and refurbish severely corroded components of the TBM while in the tunnel, resulting in a successful re-launch in April 2014. The Herculean efforts required by all of those involved are documented herein.

REDESIGNING THE CHANNEL

Construction of the siphon tunnel is part of a much larger project. The Anchorage Channel, an integral part of the shipping trade with access to New York Harbour and the rest of the Port of New York and New Jersey, is one of the more heavily used water transportation arteries in the world. Future cargo volumes are expected to double over the next decade and possibly quadruple in 40 years. The channel must be deepened in order to accommodate the new generation of cargo mega-ships, which have drafts that exceed 14m/46ft (the present depth of Anchorage Channel), and ensure the City's ability to benefit from the anticipated increase in this sector of the economy.

Using funding authorised by the Federal government, the Port Authority of New York New Jersey (PANYNJ) and the United States Army Corps of Engineers (USACOE) proceeded with dredging operations to deepen the Anchorage Channel to 15m (49ft) below mean low water over a length of 5,800m (19,000ft), from the Verrazano-Narrows Bridge to the channel's confluence with the Port Jersey Channel.

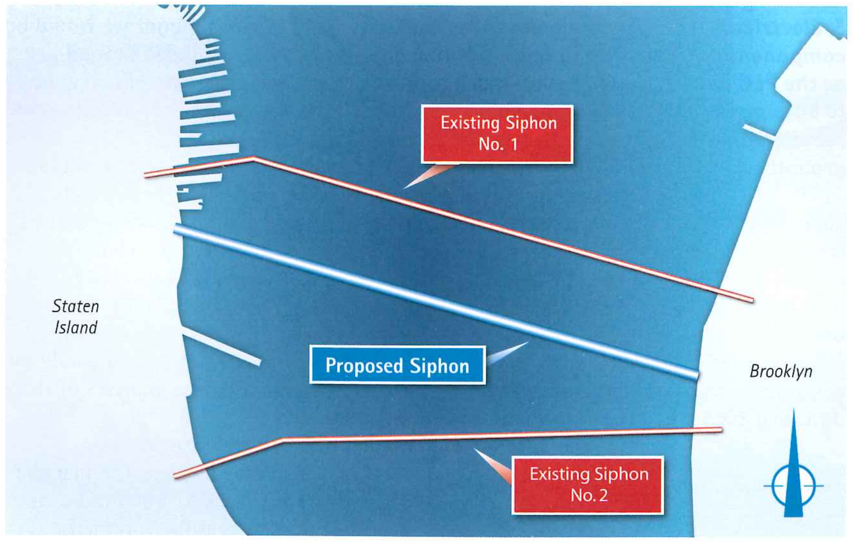
Below (left): Figure 1, Location of proposed siphon in New York, USA

Right: The 3.8m EPBM, manufactured by Caterpillar, was launched in August 2012

In order to complete their project, however, the two existing siphons owned by NYCEDC had to be removed, ultimately requiring replacement by a larger tunnel. The new siphon required a 3.6m (11.8ft) diameter, 2,883m (9,458ft) long tunnel. NYCEDC was responsible for the construction of the USD 300M project on behalf of the New York City Department of Environmental Protection.

The new siphon will be finished with a backfilled 1.2m welded-steel water pipe. Full backfill around the riser pipes in the shafts will also be installed. Water transmission mains connecting the tunnel to the existing system will be constructed in open cut. Microtunneling machines will drive two additional crossings, about 99m and 37m long, under the Staten Island Railroad.

Once the new tunnel is complete, the existing siphons will be decommissioned and abandoned. The new tunnel will



serve as a backup to the 900ft deep Richmond main water tunnel that was built under the harbour between Brooklyn to Staten Island in the 1960s through hard rock.

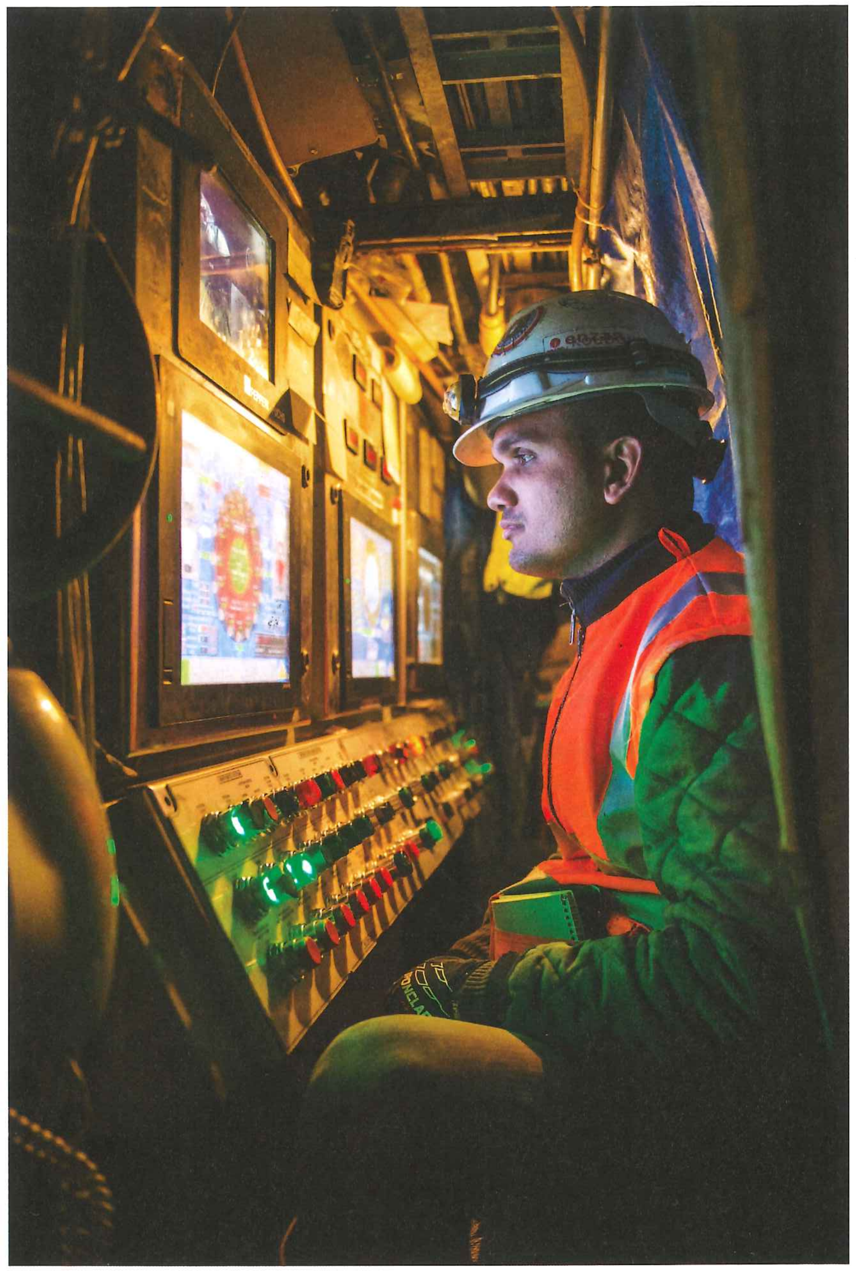
STARTUP AND FLOOD

Tully/OHL USA JV procured a 3.8m (12.5ft) diameter EPB TBM from Caterpillar in 2012 to bore the new siphon tunnel. The TBM, dubbed "Pat", was designed to drive through highly variable clays, sands, weathered rock and boulders. "The contract allowed for both EPB and Slurry. The geology of the project, with around 75 per cent excavation in clay, was more favorable for an EPB machine," said Luis Alonso, Tunnel Manager for OHL. It was launched from the 35m (115ft) deep Staten Island shaft, boring towards the 40m (131ft) deep Brooklyn shaft, in August 2012. An onsite crew from the local tunneling union, known as the Sandhogs, assisted OHL in the tunnel construction.

The project started off well, but in October 2012, the unexpected happened: a massive hurricane, dubbed Superstorm Sandy, barreled down on the U.S. East Coast with winds up to 145 kph (90 mph). Extreme flooding at the waterfront jobsite in Staten Island overtopped protective concrete barriers that had been designed 1m (3ft) above the 100-year flood level. Seawater rushed into the tunnel and the nearly 113m (370ft) long machine was entirely submerged after boring only a few hundred meters. "Obviously this was our biggest challenge," said Alonso. "After that, not many people thought we would be able to finish this tunnel." The damage extended beyond just the jobsite–much of Staten Island is a designated flood zone and many businesses, homes, and major pieces of infrastructure had been substantially compromised.

"It was a shock for us," continued Alonso. "No one could imagine something like that happening." After floodwaters began to recede and some additional water had been pumped from the tunnel, OHL set about determining the extent of damage on the machine. There had been one cutterhead intervention just two weeks prior to the flood, so there was some confidence that even though the machine had been stalled in the tunnel at earth pressure, the cutterhead would be in good shape. Crews entered the tunnel to do analyses of the bearing cavity and rotary union.

The TBM was determined to be severely corroded by saltwater, and extensive rebuild would be needed. The machine sat idle until July 2013. During that time, CAT announced its impending closure of its TBM business, and the contractor



Above: Figure 3, Electrical components such as the PLC had to be completely rebuilt from the ground up

Left: Figure 4, A tunnel worker checks the TBM as it begins boring into the slurry wall of the exit shaft, January 2015

Above: *Figure 5, Workers from the Sandhogs union take a moment to celebrate as the EPB hits the slurry wall of the exit shaft - the start of the final stretch of tunneling - in January 2015*

Above (right): *Figure 6, A tunnel worker cleans the tunnel invert behind the TBM.*

looked to other manufacturers. "OHL was always determined to finish this project. After studying other options, we decided to proceed with the full refurbishment of the TBM. The whole crew worked together to achieve that goal," said Alonso.

EXTENSIVE REBUILD

Robbins arrived onsite in July 2013 to begin the assessment. The general plan for the refurbishment centered on removing the rear eleven gantries and belt conveyor from the tunnel and shipping them by truck to an offsite facility where the backup gear could be completely cleaned, evaluated and repaired. The remaining two gantries, screw conveyor, segment erector, stationary shield and forward shield would have to be refurbished onsite in the tunnel. The segmented concrete lining would not permit the removal of these items.

Per the scope of work, the cutterhead and main bearing of the TBM were excluded from the refurbishment, as they were under earth pressure and not accessible. The Robbin team would need to complete the refurbishment taking into account unknowns, such as the condition of the cutterhead, and the thrust cylinders, as the machine had stalled at pressure with the thrust cylinders retracted.

The parties involved set about immediately on a two-pronged approach of shipping the removed equipment to the manufacturer's facility in Solon, Ohio and organising a plan for the onsite refurbishment of the remaining items. By early August, the gantries were back in Solon and production was proceeding to inspect and disassemble equipment in order to evaluate and order items where necessary. Onsite, local 15 mechanics and local 147 sandhogs worked diligently identifying, disassembling and evaluating system components.

"We had to be absolutely vigilant about the earth pressure of 3 bar, as we were doing much of the rework inside the tunnel. There were some components we were simply not able to reach, such as the screw conveyor doors and guillotine door, as these were under pressure," said Roger Cope, Robbins Field Service Technician, who was at the site throughout the refurbishment until breakthrough. Major failed components, such as grout pumps, drive motors and propulsion hydraulic blocks were shipped by truck back to Solon for repair, while less complicated items were ordered for shipment directly to site. Additionally, a local hydraulic supply house was selected to provide onsite hose making capabilities up through 50mm (2 inches) diameter. In this way, replacement of worn hoses could be produced as needed, saving precious time.

By September, 2013, the gantries in Solon were being refitted, while onsite the bulk of the evaluations were complete and workers turned to cleaning and re-hosing the forward shields and first two gantries. Steel components of the machine were stripped with abrasives, then sanded and repainted. However, the challenges were just beginning.

REVERSE ENGINEERING

The Robbins crew was additionally contracted to guide onsite personnel in replacing corroded hydraulic components and all new electrical—from Variable Frequency Drives to PLCs and wiring—inside the small tunnel. "We had some manuals, but no autoCAD drawings and no supporting materials from the manufacturer. We had to identify each component and reorder it. The PLC took the longest by far," said Bogdan Tudor, Robbins Field Service Technician. Essentially the crew had to observe how the TBM worked and create a detailed report to redesign the system from the ground up—from the segment operation to steering control and more.

One major difference was the steering between Robbins EPBs and CAT-designed EPBs. "Robbins EPBMs use quadrant steering. The CAT machine, however, had 16 cylinders, each independently operating with its own controller." That required researching

and designing a system the team was initially unfamiliar with, in addition to other challenges. "There were other things like the flowmeters, which monitor critical flows in the lube system, that weren't responding. The physical components of the meters interact with a card, and we determined that since we had gotten a new PLC from another manufacturer, the original cards didn't interact with it. We needed to determine which cards would interact with the PLC and replace them," said Tudor. The entire conversion and rebuild of the electrical system required a team of six electricians and took about four months.

THE RESTART

In the final phase of the refurbishment, a Robbins PLC technician was able to complete the commissioning of the TBM and on April 14, 2014 the machine officially returned to mining. To ensure continued success, the team remained on site to support ongoing maintenance of the TBM. In the coming months, the machine performance steadily increased, eventually reaching as high as 100ft (30.48 m) per day in August 2014. This result–the equivalent of 25 rings in 24 hours–significantly outperformed the machine as designed before the flood, which had a maximum of 16 rings per day (segment rings are 5+1 precast concrete, 1.2m in length).

By August, the project appeared to be on target for a mid-September completion. However, in early September, ground conditions changed from marine sediments (clay, silt and sand) to glacial geology with sand, exceptionally hard boulders, and excessive water ingress, resulting in slow propulsion rates. "The TBM needed more thrust and we decided to implement four additional auxiliary cylinders. Robbins field service helped in developing the size, features and location of the cylinders, which were eventually placed in the lower quadrant of the propulsion system," said Alonso.

After installing the 50-ton auxiliary cylinders in the lower propulsion system, crews were able to re-establish forward progress but at a reduced rate. The TBM pushed on, but in early October the project was faced with another hurdle. The machine encountered a pocket of glacial soils comprised of larger, hard stones. The hardened material led to tool failure and the TBM was stalled for the majority of November while a hyperbaric intervention at 4 bar was performed to install new tooling. With the intervention complete and a new dressing of rippers installed, the TBM began mining again in late November. Despite the obstacles, the crew was able to steadily increase the rate of excavation to 5 to 7 rings per day.

Once mining was reestablished, the TBM faced a final critical crossing beneath Belt Parkway, a busy thoroughfare built on sensitive harbour-side soils. Monitors were installed in the roadway and around critical utilities including a high-pressure gas line to make sure settlement remained within the set parameters as the machine passed 34 m (112ft) below. As crews mined, they injected polymer to maintain a smooth flow of muck and consistent earth pressure, while pre-mixed single component grout was used for backfill of the annular gap. The grout was delivered via grout pumps to ports behind the segments at the edge of the tail shield. Ultimately, the crossing was successful and monitored settlement was well within specified limits.

Above (left): Figure 7, The harbour-side jobsite, now rebuilt, was inundated by Superstorm Sandy in 2012 when flood barriers that were designed as 1m above the 100-year flood level were overtopped by seawater

Above (right): Figure 8, Precast concrete segments being transported into the tunnel to build the final rings, January 2015

BREAKTHROUGH

By 24 January 2015 the machine had mined through the first 1m thick slurry wall of the exit shaft. Its completion point was just beyond the sand-filled exit shaft, past a second slurry wall where the TBM would be buried. The final metres were completed days later on 28 January. The completion of the project marks the first successful excavation by an EPB in the NYC area.

"This tunnel is an important part of a larger project, and we are proud to be doing what we do every day, dealing with troubles as they come up, until we reach the end of the drive," said Alonso.

"With tunneling complete, the stationary and tail shields were buried at the exit shaft entrance, with the cutterhead and back-up removed

THE ROLE OF INVERSE ANALYSIS IN TUNNEL DESIGN

In this paper, **Angelos Gakis, Stephen Flynn, Ali Nasekhian, and Panagiotis Spyridis**, all of *Dr Sauer & Partners* look at the use of inverse analysis of finished tunnel structures, and the verification of models in modern tunnel design. This article also uses the underground structures of Crossrail's Farringdon Station in London, UK as a case study to illustrate the process

IN MODERN design of complex tunnelling projects it is best practice to utilise 3D finite element analysis (3D FEA), its main advantage being the ability to capture the impact of the actual construction processes and the very significant three-dimensional effects. The latter may include the effect of tunnels constructed in close proximity, the interaction with existing structures and the non-homogeneity of the ground conditions.

On the other hand, 2D finite element analyses (2D FEA) can be employed for the execution of simplified, quick models which, as long as the engineer is fully aware of the assumptions and the limitations involved, can prove to be a very useful means of calibrating, supplementing and in some cases substituting the demanding 3D models.

An important question at the beginning of a design project is therefore which type of analysis should be applied. To provide a case example, the authors will consider Crossrail's Farringdon underground station which is presented in the following sections.

The Crossrail project comprises a combination of long TBM drives forming the running tunnels with sprayed concrete lined (SCL) tunnels forming the station layouts. In principle for such a project, 2D FEA can be used for the design of the running tunnels but inside the footprint of the stations, 3D FEA are necessary for the aforementioned reasons.

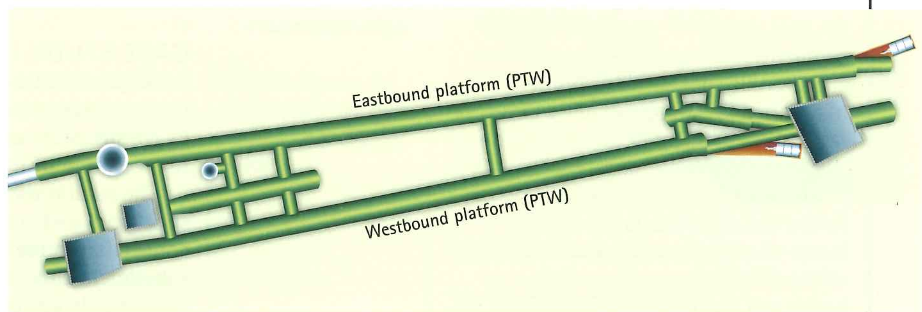
There are additional aspects of the design that may need to be considered, such as:

- Sensitivity analyses to assess the weight of several parameters
- Coupled effective stress/pore water pressure analysis
- Consolidation analysis
- Advanced constitutive soil models
- Advanced concrete models
- Excavation sequence (i.e. exact simulation of face divisions for SCL tunnels)

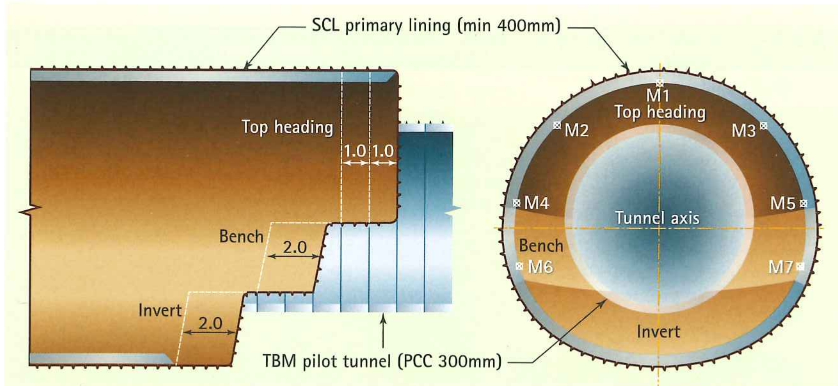
However, realistically these cannot all be incorporated in a 3D FEA due to the limited time frames and resources.

The following sections present a combination of 3D and 2D FEA that has been used to back analyse the actual performance of the SCL tunnels.

The findings of this exercise as well as the importance of the inverse analysis in tunnel design are highlighted in the context of practical FE modelling.



Above: Figure 1, Farringdon Station layout



Below: Figure 2, Typical excavation and support sequence showing the typical layout of a monitoring cross section. It is 11.35m wide by 10.66m high (excavation line)

THE ROLE OF INVERSE ANALYSIS

Inverse or back analysis is a commonly used practice in civil engineering, widely applied in slope stability problems and could be defined as the execution of an analysis (finite element, limit equilibrium etc) where the problem parameters are varied accordingly until a known result is derived. These parameters that lead to the correct (or known) solution are called 'back analysed' and the model is accordingly calibrated.

A good example on the application of the back analysis with respect to the 3D effects in slope stability comes from Duncan and Wright [2]. A slope stability problem is in most cases analysed using 2D limit equilibrium analyses (or/and FEA) where a factor of safety is calculated.

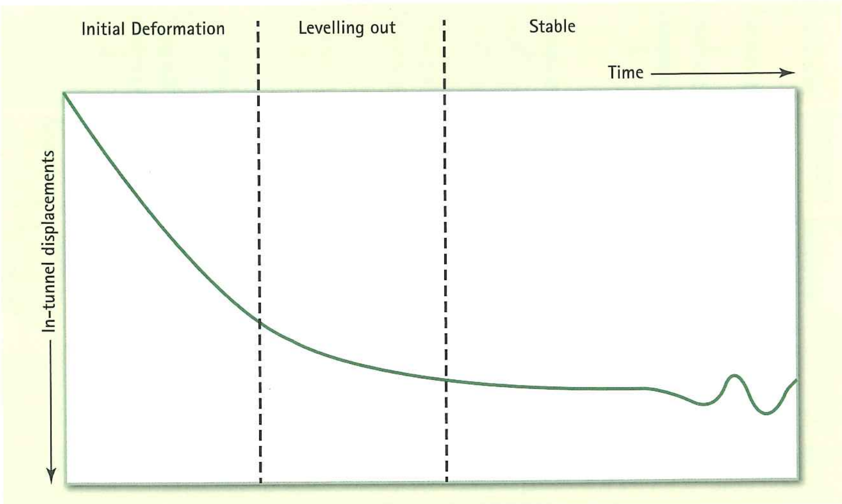
However, this approach excludes the very important 3D effect, i.e. the geometrical characteristics of the slope and the side shear (ratio width/length). In a normal analysis, excluding these factors would result in the calculation of a conservative factor of safety.

However, in a back analysis (where the slope has failed and the factor of safety is unity), exclusion of the 3D effects would result in higher soil parameters along the slip plane, therefore in an unconservative assessment

Similar considerations are valid for tunnel design. Inverse analysis in tunnelling projects can be performed by varying parameters appropriately in order to derive the deformations observed through in-tunnel or surface level monitoring. The parameters that can be varied in a finite elements model may include the strength/stiffness of the soil or concrete, the simulation steps, the geometry of the finite elements mesh etc.

Two very important aspects that the authors would like to make note of are:

- The variation of the parameters should be in a natural scale range.
- The back analysis should not try to be conservative or unconservative but simply should try to replicate the actual behaviour as closely as possible.



Above: ***Figure 3, Typical phases in a time plot of the in-tunnel deformations***

CASE STUDY: FARRINGDON STATION

Farringdon station will provide interchange between Crossrail, London Underground and Thameslink rail networks. During its construction, an important role that the station had was the reception of the two westbound and eastbound TBMs.

The station was constructed at approximately 30m below street level and comprised two ticket halls that provided connection to the platform level via two escalator inclines with subsequent concourse tunnels, two platform tunnels enlarged from the already constructed TBM tunnels, approximately 300m long each, and multiple cross passages and ventilation tunnels.

The main contractor Bam, Ferrovial, Kier joint venture (BFK), was awarded the contract (C435) by Crossrail. BFK employed Dr Sauer & Partners (DSP) as their SCL specialist.

Two special features related with Farringdon Station were:

- The construction phasing of the platform tunnels: they were enlarged using SCL methods from the existing TBM tunnels.
- The tunnels were constructed mainly in the Lambeth Group formation, a mixture of very stiff over consolidated Clays which constituted an excellent open face tunnelling medium with the exceptions of the interbedded sand lenses with water pressures that added a certain level of difficulty and risk to the SCL tunnelling operations.

IN-TUNNEL MONITORING ANALYSIS

The deformations of the approximately 1km of SCL tunnels in Farringdon station were monitored using a high precision total station to survey monitoring targets. These targets were installed at predefined monitoring cross sections (MCS) generally spaced every 10m.

The typical layout of a platform tunnel monitoring cross section is shown in Figure 2 (page 35).

Absolute deformations of each target were acquired on a daily interval following the construction of the tunnel section at that chainage.

Three phases can be distinguished in a typical time plot of the in-tunnel deformations as shown in Figure 3:

- The initial deformation phase starts with the first readings and lasts for three to five days, exhibiting almost linearly increasing deformations with time.
- The levelling out phase starts with the ring closure, where the in-tunnel deformations clearly start levelling out and lasts for another three to five days.
- The stable phase then follows where in the absence of subsequent tunnel excavation in the proximity, only minor fluctuations of the readings are expected.
  These fluctuations are not related to actual lining deformation but are a result of other factors such as the monitoring accuracy, temperature changes, construction vibrations etc.

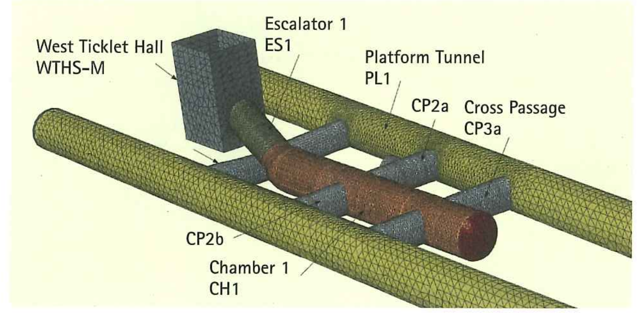
A very dense network of compensation grouting arrays (tub-a-manchettes or TaMs) was installed in Farringdon, covering a large portion of the station's footprint.

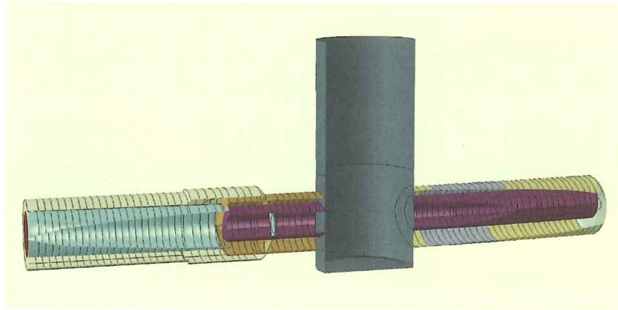
In order to exclude the effect of compensation grouting in this paper, the average in-tunnel deformations of the parts of the two platform tunnels (Eastbound and Westbound) that were not covered by TaMs were derived and summarised in Table 2 (see below).

Table 1. Geotechnical parameters considered in the study

Soil Properties	Upper Strata	London Clay	Lambeth Group	Thanet Sand
Unit Weight [kN/m³]	17	20	21	21
Young's Modulus [MPa]	10	40+3.7z	36+5.9z	209+4.3z
Poisson's Ratio [-]	0.2	0.495	0.495	0.2
Undrained Shear Strength [kPa]	N/A	85+6.5z	95+10z	N/A
Friction Angle [o]	31	0	0	39
Earth coeff at rest. k_0	0.5	1.2/0.6	1.2/0.6	1.0

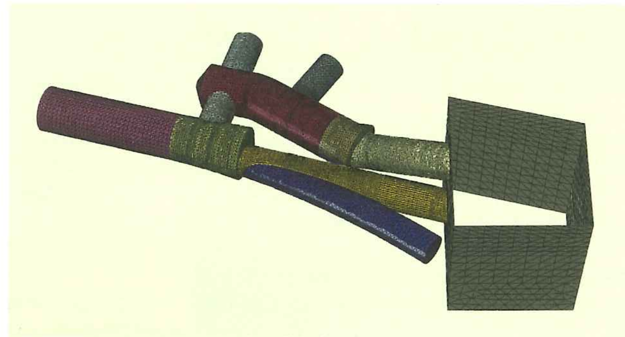
Source: Dr Sauer & Partners



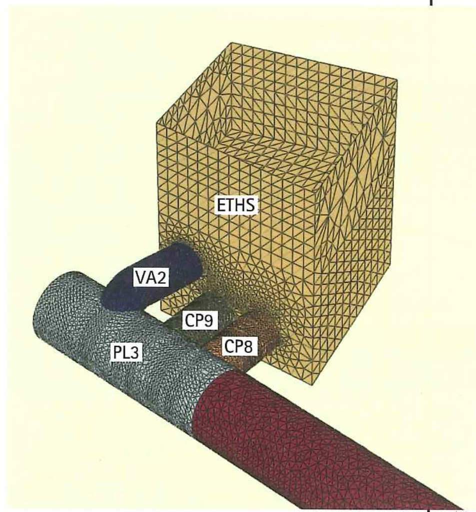


Above (left): ***Figure 4a, FE design model of West Ticket Hall***

Above (right): ***Figure 4b, SCL access shaft area***



Left: ***Figure 4c, Model of East Ticket Hall***



Right: ***Figure 4d, Triple connection to the East Ticket Hall***

3D FE DESIGN MODELS

Due to computational efficiency reasons, a decision was made to divide the temporary SCL tunnels in Farringdon into separate, smaller 3D FE models. The four main models are shown in Figure 4, namely the West ticket hall area model, the East ticket hall area model, the SCL access shaft area model and the triple connection to the East ticket hall.

These individual models were created to address and tackle particular design issues and challenges. Three dimensional modelling provided an opportunity to consider the 3D effects of tunnelling in the course of construction, ground/structure interaction, face stability deriving information regarding volume loss and ground movement without subjective assumptions.

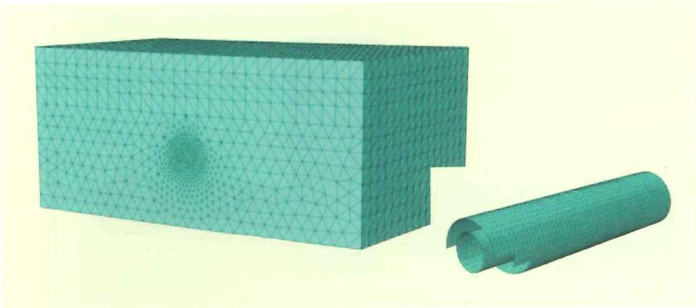
The purpose of the 3D FE design analyses in this project was to dimension the lining thickness at complex situations (e.g. a triple junction, when at a close close proximity to other tunnels etc), to optimise the temporary works excavation sequences and providing trigger values for monitoring purposes.

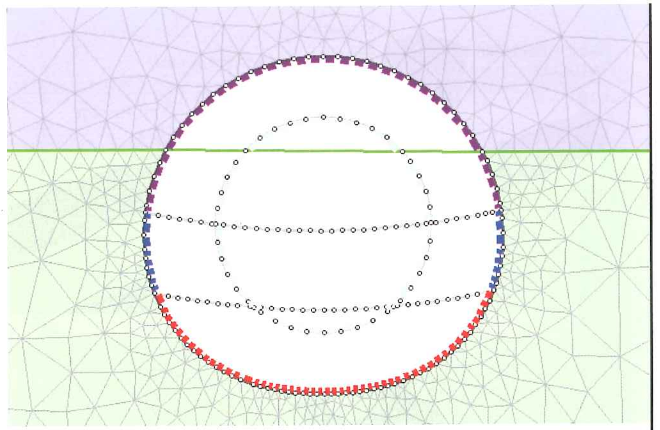
ABAQUS Version 6.12 (Dassault Systemes Simulia)[1] a general purpose finite element software package was used to perform the numerical analyses.

Table 2. Average in-tunnel deformations in TaM-free sections

Average Vertical Displacements (mm)			Average Transverse Displacements (mm)		
M1	M2/M3	M4/M5	M1	M2/M3	M4/M5
12	13	13	0	4.0	7.5

Source: Dr Sauer & Partners





Above (left): ***Figure 5a, 3D FE back analysis model***

Above (right): ***Figure 5b, 2D FE back analysis model***

Below: ***Figure 6, Comparison of the actual average and the predicted in-tunnel deformations***

Soil materials were modelled with the elastic-perfectly plastic Mohr-Coulomb model. For the purpose of the primary SCL design no groundwater pressure was applied in the analysis since the primary lining is not considered to be watertight. Undrained soil parameters were taken for the analysis in order to account for the 'fast' construction effects in comparison to the time of consolidation in the London Clay.

The numerical analyses have been undertaken on the basis of a total stress analysis. Both undrained shear strength (Cu) and Young's modulus (Eu) of the clay stratums increased linearly with depth.

Additionally, two main characteristics of the geology in Farringdon, both the presence of the faults and the variation of the thickness of the London Clay, have been simulated in these models.

The fibre reinforced sprayed concrete (SFRC) was modelled as a linear elastic – perfectly plastic material considering the post failure material behaviour determined by residual flexural tensile strength of SFRC.

In all the models, the simulation of the sequential excavation and lining installation followed a multi-step analysis based on the designed excavation and support sequences. The excavation and lining installation of one advance was performed in two steps; i.e. the soil was removed in the first step and the lining was installed in the second step.

All the major excavation sequences (top heading, bench and invert) in large tunnels such as platform and concourse tunnels were simulated according to the drawings while in small size tunnels (e.g. cross passages) a full face method was considered.

BACK ANALYSIS OPTIMISATION

Both 2D and 3D FEA were used to perform inverse analysis. The main scope of the 3D FE back analyses was to assess the effect of the type of the simulation of the excavation, ie between a full face excavation and the actual division of the face in top heading, bench and invert.

For this purpose, a more simplified 3D model (see Figure 5a) was constructed where one platform tunnel was excavated following various excavation sequences, namely:

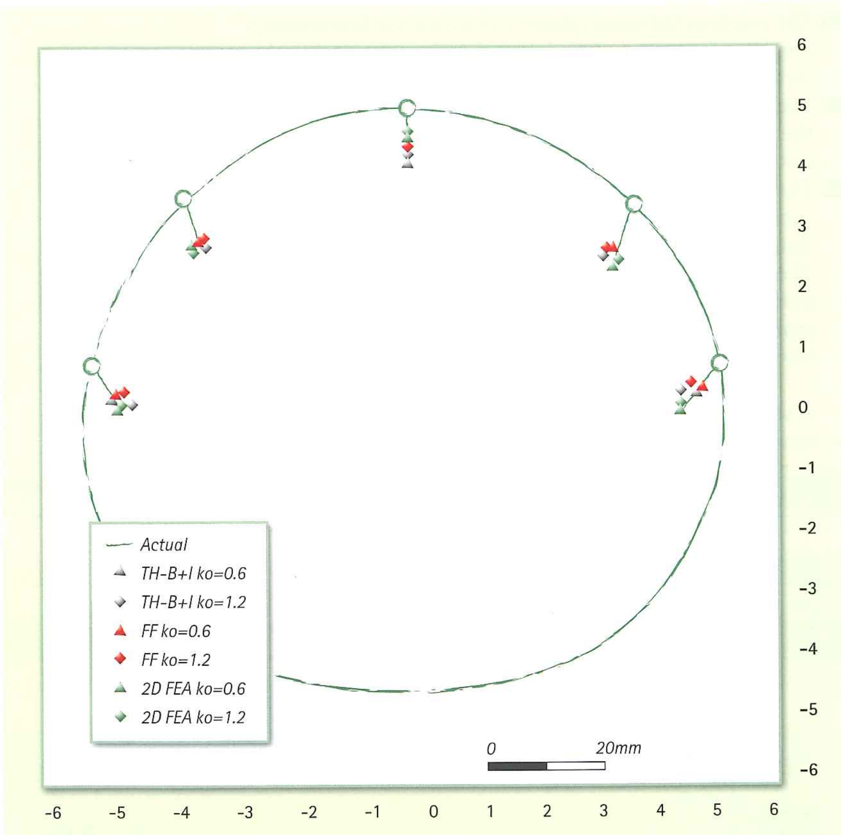
- Two top headings, bench, invert (TH-B-I)
- Two top headings, invert, bench (TH-I-B)
- Two top headings, combined bench and invert (TH-B+I)
- Full face (i.e. 1m rings)

All top heading steps were 1m long and all Bench/Invert excavation steps were 2m long.

The first important conclusion was that the difference between the TH-B-I, TH-I-B and TH-B+I simulations was minor, therefore the simpler TH-B+I simulation was used instead.

A simplified 2D FE model (Figure 5b) was also constructed in order to assist in the multiple back analyses.

The general steps of the simulation were the following:



1. Geostatic stress state
2. Softening of subsequently excavated TBM tunnel area by 50 per cent
3. Installation of TBM lining and removal of softened soil
4. Simulation of the stepwise excavation of the Platform tunnel

COMPARISONS

The calibration of the back analysis models assumed the following three factors:

- Predict the in-tunnel displacements as accurately as possible
- Predict the surface settlements as accurately as possible
- Avoid underestimating the lining stresses

For the in-tunnel displacements comparison, the average values as shown in Table 2 (page 37) were used.

Figure 6 (page 38) shows the results for 2 different values of the earth coefficient at rest (k_0) of the 3D FE design models (FF k_0=0.6 and FF k_0=1.2), the back analysis 3D models (TH-B+I k_0=0.6 and k_0=1.2) and the 2D FE back analysis models.

It is shown that the analyses with k_0=1.2 overestimated the transverse displacements and underestimated the vertical displacement of the crown. Both the 3D FEA with TH-B+I excavation and the 2D FEA with k_0=0.6 showed an excellent match with the in-tunnel displacements. Similar results have been presented in[3] [4].

For the comparison of the surface settlements, one of the very few continuous monitoring arrays where no compensation grouting was carried out was chosen. The accuracy of the models with k_0=0.6 as compared to the ones with k_0=1.2 is shown in Figure 7.

Although the actual performance of the surface was very stiff, possibly affected by the existing foundations, the 3D and the 2D FE model with k_0=0.6 produced more satisfying settlement troughs, which correspond approximately to a volume loss between 0.4 and 0.5 per cent.

These values correspond only to the enlargement from the existing TBM tunnels using SCL methods, thus excluding the volume loss induced by the TBM excavation.

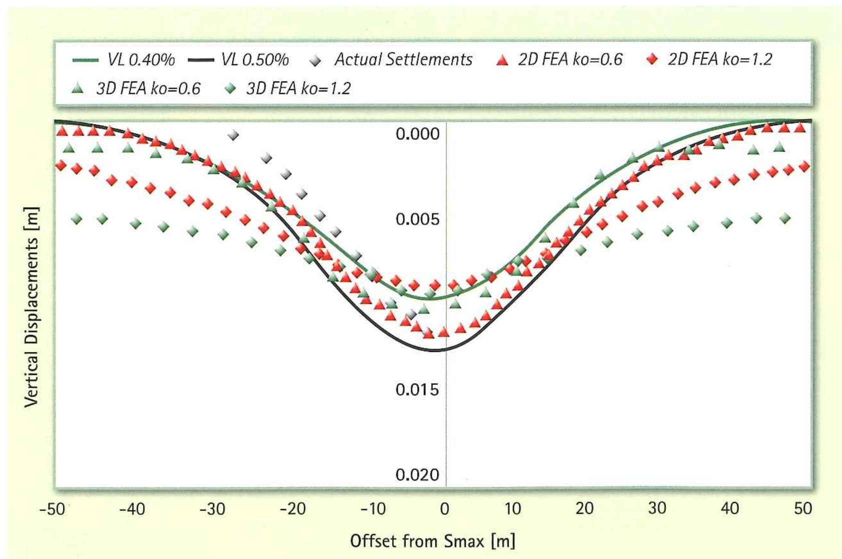
CONCLUSIONS

From the 3D and 2D FEA that were utilised to perform the back analyses in Crossrail Farringdon station, the following important conclusions could be drawn:

- The prediction of the surface settlement is very sensitive to the ko value.
- In a 3D FE analysis, the division of the excavation sequence in Top Heading, Bench and Invert produces similar results in-tunnel displacements and lining stress results if the bench and the invert are combined into one step.
- Both 3D FE analyses simulating a full face excavation (FF) and a divided TH/B/I excavation produce very similar settlement troughs. For this purpose, the more simplified FF simulation can be used.
- For the ground conditions in Farringdon station, a value of k_0=0.6 produced more realistic deformation results (in-tunnel and surface settlements).
- The volume loss attributed solely to the SCL enlargement of the Platform tunnels from the existing TBM tunnels in Farringdon, varied between 0.4 per cent and 0.5 per cent.
- The 2D FE back analysis, predicted both in-tunnel and surface settlements very reliably. This was expected at some extent as the spans of the platform tunnels between junctions were long enough to be able to approximate plain strain conditions.

Simple 2D or/and 3D calibration models can be utilised in order to derive similar valuable information that may increase the performance and reliability of large scale 3D FE models

The authors would like to express their appreciation for the contribution, collaboration and guidance from the Bam Ferrovial Kier contracting joint venture, Crossrail and Dr Sauer and Partners.



***Below:* Figure 7, Comparison of the actual and the predicted transverse settlement troughs. Different volume loss curves are also shown**

References

[1] **Dassault Systemes** Simulia 2011. *ABAQUS Analysis User's Manual-V6.12*
[2] **Duncan, J.M. & Wright, S.G.** 2005, *Soil strength and slope stability*, John Wiley & Sons
[3] **Gakis, A., Flynn, S. Nasekhian, A.** 2014. *Back analysis of observed measurements for optimised SCL tunnel design.* North American Tunneling: 2014 Proceedings
[4] **Gakis, A. 2014.** *Design of a SCL wraparound tunnel utilising a 3D geological model for Crossrail Farringdon Station.* BTS Harding price 2014 finalist paper. (please see in www.britishtunnelling.org.uk)

WTC CROATIA

The **World Tunnel Congress** heads to the Dalmatian Coast for the first ever visit to South East Europe region. As of 2013, Croatia is the newest member of the European Union, giving this WTC a timely aspect

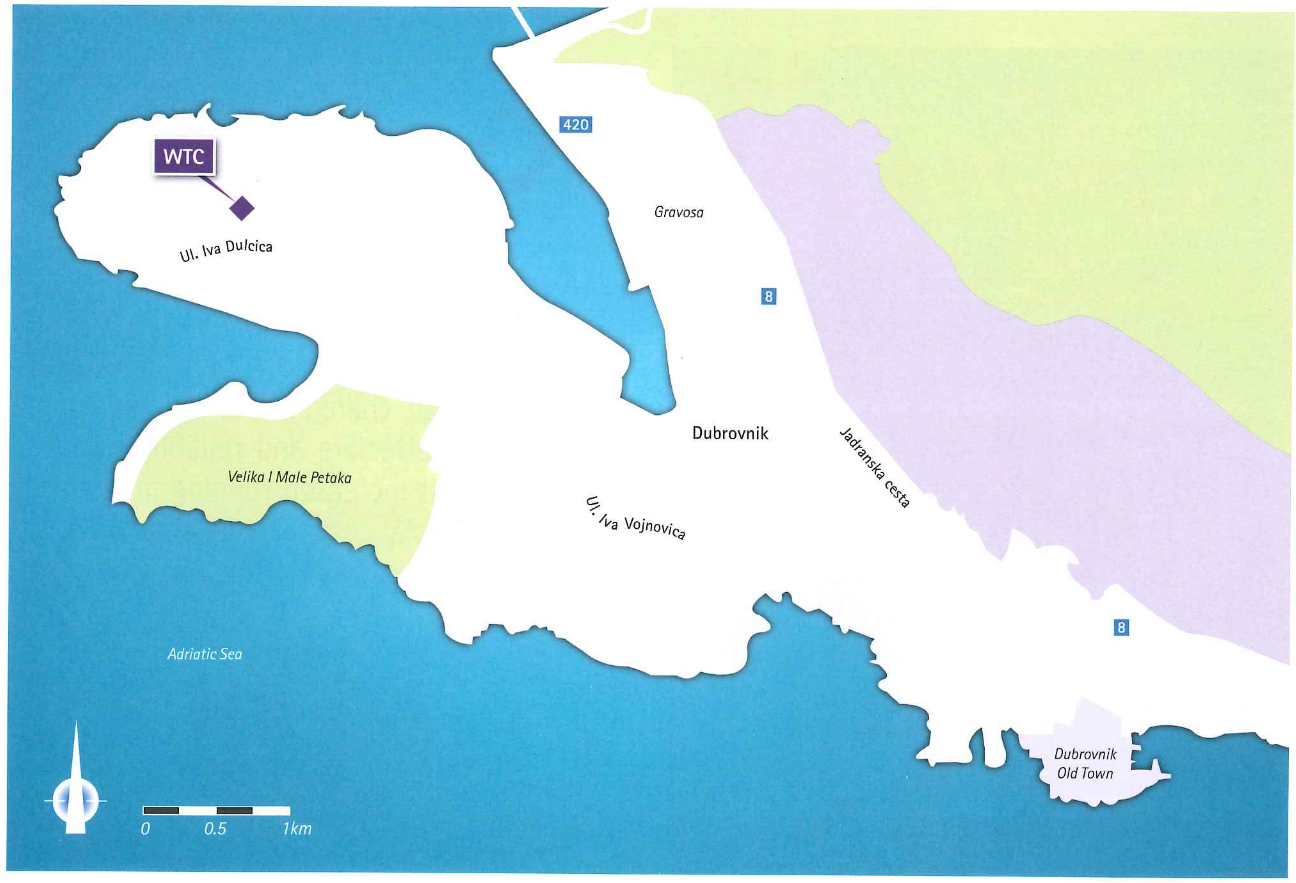
WTC 2015

Dubrovnik, Croatia
Valamar Lacroma Dubrovnik Hotel Conference Hall and Business Centre
22-28 May
www.wtc2015.com

Currency

Croatian kuna (HRK)
GBP 1 = HRK 10.58
USD 1 = HRK 6.89
EUR 1 = HRK 7.58

CROATIA IS is located in the middle of South-East Europe and on the July 1st, 2013, Croatia became the 28th member of the EU. South-East Europe is the EU region with the highest expectations and plans in developing infrastructure in next two decades in Europe. Therefore choosing Dubrovnik with its location in the middle of the South-East Europe region and in the heart of Europe we would like to make the sign to all other member nations where to go and where to intensify their activities in the soon future. So far none of SEE countries have had opportunity to organise a World Tunnel Congress and this happening will strongly and certainly help further development of underground infrastructure in the future. Dubrovnik is also a regional centre for infrastructure works with unique underground solutions (underground HPP Ombla, city road tunnel, light rail to airport, new road roundabout) that will all be in construction in 2015



WHEN THE GROUND GETS TOUGH

Rhian Owen explores TBM cutter options with a focus on mixed ground

Rhian Owen
Rhian has been a regular contributor to *Tunnels and Tunnelling* since 2011

THE MOST difficult terrain for TBM tunnelling is mixed ground. It's a challenging prospect, which can involve excavation in boulder fields, sections of rock, sticky clay, often under high water pressure or changing water pressure. The right cutting tools and cutterhead design is therefore vital in maintaining a rapid advance rate.

The choice of cutting tool is dependent on the anticipated geology. However, disc cutters and knife bits are the primary tools of choice for EPB machines with other add-on tools supporting the functioning of these tools.

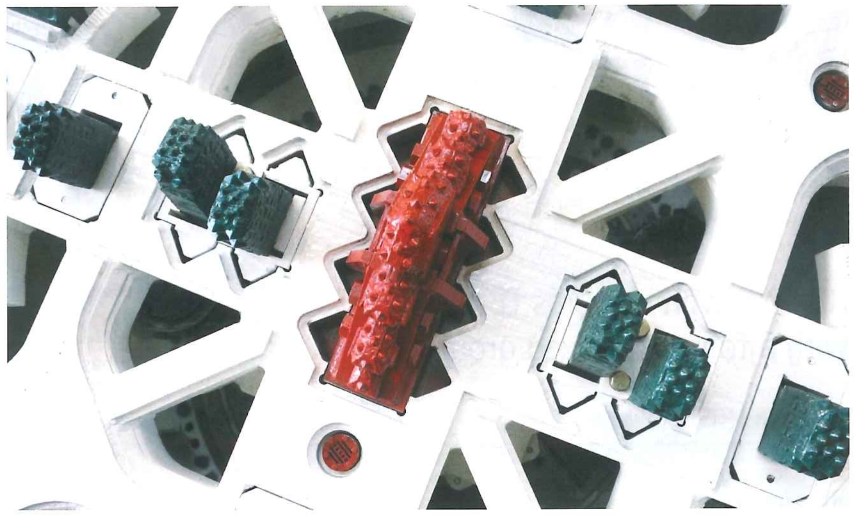
The optimal primary protection for EPB cutterheads in soft and mixed ground is the replaceable knife bit. "These come in standard duty and heavy duty, but standard duty is only recommended for geology that is very easy to excavate," says Brad Grothen, engineering manager for Robbins. "Although these tools are replaced relatively quickly and easily once they are accessed from behind the cutterhead, they require interventions to inspect and replace; thus, it is better to choose the highest quality knife bits in order to minimise required changes."

Grothen adds that common knife bits include eight layers of tungsten carbide inserts, a proprietary alloy steel shank, and a complete coating of 64 Rockwell C (Rc) hard facing. These replaceable knife bits are welded to a base plate assembly that is wedge-locked into the cutterhead.

Mixed-face EPB cutterheads are designed to accept either disc cutters or knife bits. "In pure EPB applications, it is

An example of a hybrid TBM optimized for hard rock conditions at Australia's Grosvenor recommended to add shorter secondary knife bits in the same path with the primary knife bits so wear doesn't rapidly advance to the cutterhead structure if the primary knife bits wear out. The secondary knife bit is essentially a shorter version of the primary knife bit.

"Cutterhead spokes are designed to alternate between primary and secondary knife bits. It has been found that a radial spacing of these primary cutting tools at a set distance apart is efficient in the breaking up of soft ground. When hard rock or boulders are encountered and these tools are replaced by disc cutters, this same spacing allows the discs to break up the rock and allow the cracked rock in-between cutters to fall out."



Above: *Lovat face ripper tooling used on Line 9 of the Beijing Metro*

TOUGH GROUND

Disc cutters were first invented for breaking rock and have the longest life of any cutting tool in rock. Over the years, disc cutters have shown to be the best choice of cutting tool for breaking rock into smaller pieces for easy removal. There are many styles of discs available and many options for the configurations of those discs on the cutterhead.

When large boulders are expected the cutterhead is typically fitted with disc cutters. However, Robbins states that when the tunnel also passes through more traditional EPB materials, it is important to maintain the cutterhead face opening ratio.

Disc cutters take up a lot of cutterhead space compared to EPB picks and bits. The design of the cutters and cutterhead take on great importance for mixed ground tunnels with a probability of large boulders. Restricting the size of rock pieces that may pass through the cutterhead is important to reducing the risk of blockage of the screw conveyor. Also, in such situations, minimising wear is imperative.

High performance appears to be linked to a mixed ground EPB machines being fitted with a cutterhead designed and fitted for mixed ground, for example fitted with disc cutters as well as soft ground tools.

Machines that have to be stopped one or more times in the tunnel to have the cutting head redressed, from soft ground tools to full disc cutters, under pressure often lose time for the retrofit making it impossible to achieve a rapid tunnel excavation.

"In Hybrid TBMs, the ability to manage soft ground tools and disc cutters is of primary importance. Many different cutters and soft ground tools can be used - disc cutters with carbide inserts, soft ground tooling with increasing amounts of carbide as ground becomes more challenging."

Furthermore, increasingly tough, mixed ground conditions are ushering in a new era of cutting tools. "Certainly in mixed ground hyperbaric interventions and tool changes can be a challenge, so optimising tool life and cost is important," says Grothen. More robust tool design is desirable. More hard facing, increased carbide in the tools is desired. Mounting systems must be in place, which are able to interchange between the different tool types. We want a design that is flexible in the tools that it can accommodate.

"The tools themselves can be used in a variety of mounting systems, but these need to work together to mount into a single housing."

THE HYBRID TBM

The use of hybrid TBMs is a trend that follows with the increasing frequency of difficult tunnel conditions in mixed ground conditions.

Where multiple machine types might have once been used for different sections of geology, today hybrid machines are excavating the entire tunnel.

"Hybrid TBMs are becoming more widely accepted, and are thus becoming more common," notes Grothen. "As more challenging jobs are considered, hybrid TBMs help mitigate some of that risk.

"They are being seen as a viable alternative compared to traditional solutions that might involve using multiple TBM types or combining methods like drill and blast and TBM. There are lots of ways to approach a problem of course, but Hybrid TBMs are being considered a good alternative now more than ever."

While there are various types of hybrid TBMs, the EPB/hard rock machine offers some intriguing possibilities. A cross between a hard rock single shield TBM and an EPB, these

Both: ***Workshop preparation of TBM***

TBMs bore tunnels with sections of both rock and soft ground, and utilise interchangeable cutting tools and muck removal systems to complete the project tunnel.

In terms of muck removal, Grothen says that interchangeable muck removal is what defines a hybrid TBM. Looking at a EPB/hard rock machine designed to excavate in open or closed mode, in hard rock or soft ground, Grothen explains: "This type of machine has a screw conveyor to operate in closed mode. Some machines in this category will also be fitted with a belt conveyor for better open mode performance in hard rock. In larger diameter TBMs, both conveyor types can be installed concurrently, and in smaller sizes the conveyors usually need to be exchanged.

This conversion process of course requires some amount of downtime but it can be justified if there are long stretches of rock that require the machine to be in that mode. Another feature that can greatly improve performance is use of variable speed cutter head drives with multi-speed gearboxes that can provide high torque at slow speeds for soft ground , as well as high RPM for rock.

"Cutterheads can also be designed to be converted to/from bidirectional to single direction mucking."

EFFICIENCY

The design of a hybrid TBM must be tooled for the geology in order to be most effective. Although hybrid machines provide the possibility to make difficult tunnelling projects possible, the machine must be geared towards either soft soils or hard rock.

"A Hybrid TBM is a balancing act between two different types," says Grothen. "This is particularly true of Rock/EPB hybrids and Rock/Slurry hybrids as the designs are so distinct from one another. Depending on geology, the design is then optimised to work most efficiently through the whole project. If most of the project will be in rock, for example, we will skew cutterhead design towards rock geology so it can get through short sections of soft ground while being highly efficient in rock.

"It's all a compromise, skewed for the best overall effect. Some examples of modifications for rock include abrasion-resistant wear plating installed in high-wear areas of the cutterhead, protective structures for cutters in blocky ground, and the use of disc cutters themselves."

Much of the efficiency in Hybrid TBMs, therefore, lies in the accuracy of the ground prediction.

Grothen adds: "However, If the geology is 50 percent rock and 50 percent soft ground, this will then depend on the lengths of each section. The machine will be a true compromise—and if there are very short sections of rock and soft ground switching back and forth, then the machine must be optimised towards swift conversion of muck system and cutting tools."

MEXICO'S BIG PROJECT

Work on Mexico's Emisor Oriente sewerage project started in April 2009 after decades in planning and design. The desperately needed infrastructure is designed to replace, underground, an open canal that conveys waste and stormwater from Mexico City to a discharge on the Tula River to the east of the city.

For many years engineers believed the ground would be too difficult to excavate – the soil is made up of watery clays running up to 80m deep with the water table just 2 to 3m below the surface. The ground also contains boulders up to 600mm in diameter.

Custom designed EPBs were designed for the difficult mixed ground conditions they would be facing on the job site. The machines were engineered with mixed ground, back-loading cutterheads, with carbide cutter bits to deal with variable ground conditions, and ribbon-type screw conveyors to remove large boulders.

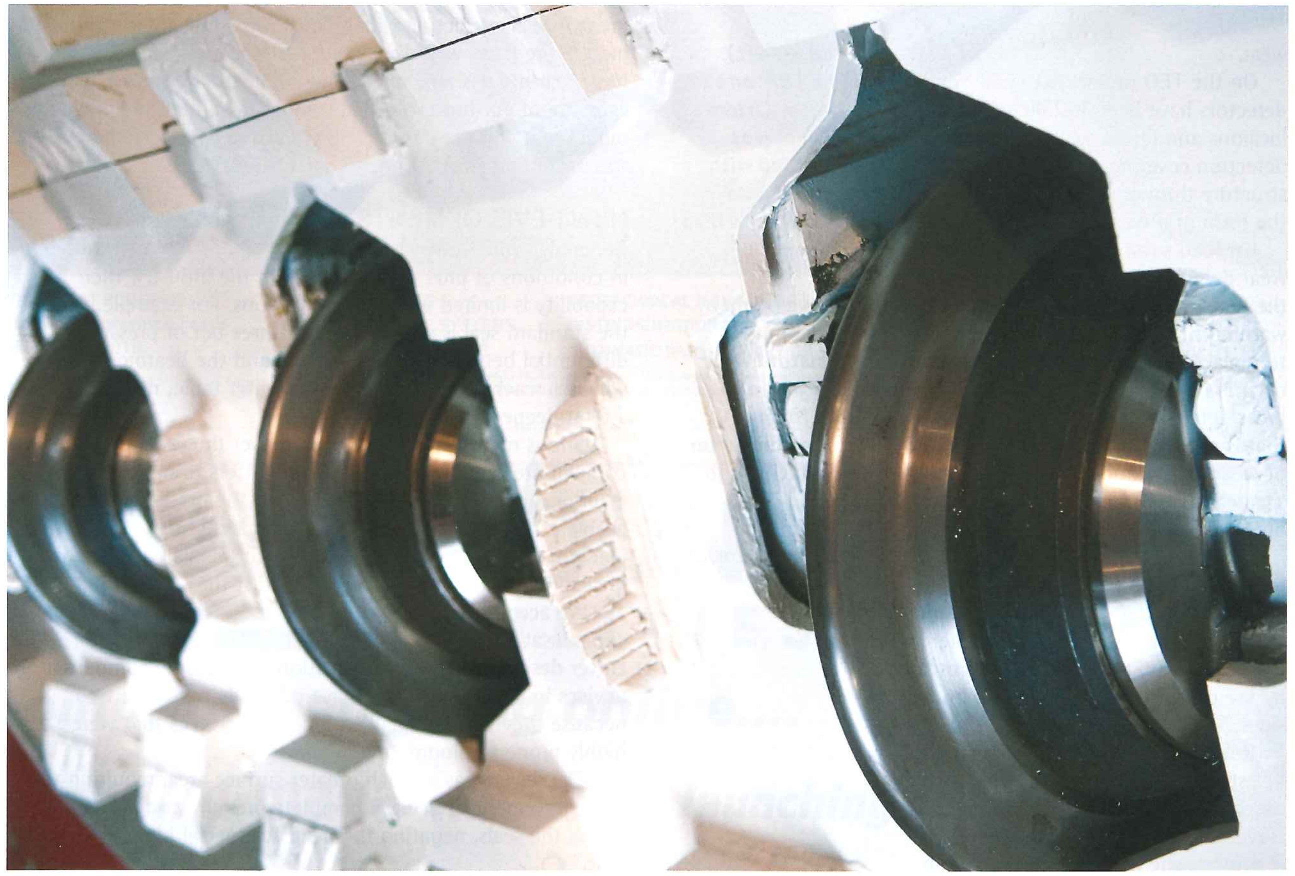
"The mixed ground heads are performing well, although the geology has changed over time and has become more challenging. The Mixed ground design has been optimized for difficult geology, but the ground is more difficult than we initially thought," says Grothen.

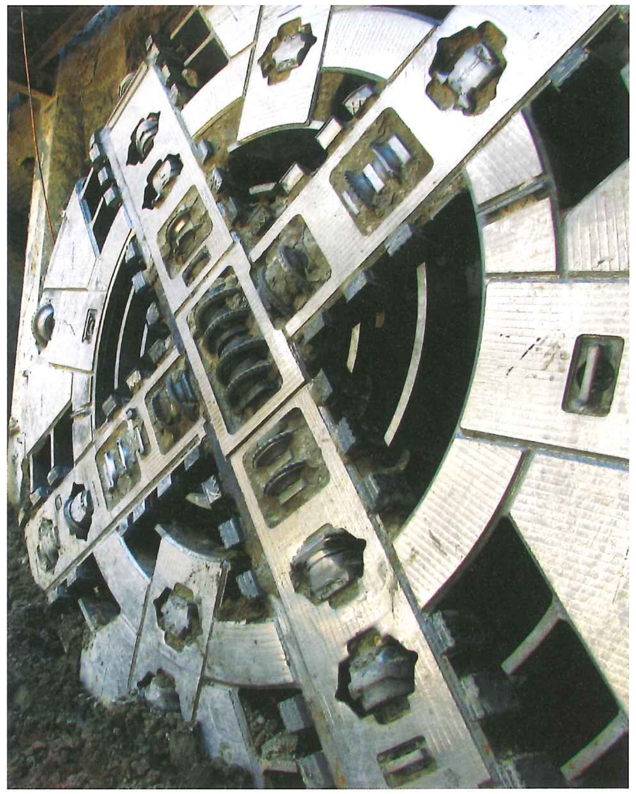
Alcala adds: "We have found during tunnelling that the ground conditions can change dramatically in as little as 50m. For this reason, we have back-loading cutterheads in order to change cutting tools safely and effectively. We are currently doing geological surveys at Lots 3 and 4, which have encountered some unexpected very hard rock conditions including abrasive basalt and boulders. We are constantly adjusting based on which points we expect the basalt to be encountered at during the tunnel drives so we can find the best way to operate the TBMs.

"Efficiency at interchanging cutters has improved dramatically throughout the project. Now that we are past the learning curve, crews can change 48 cutters in 2 to 3 days. At some points the machines are in full-face basalt so cutters can be changed at atmospheric pressure. Lot 4 did require some hyperbaric interventions using divers due to ground water."

Furthermore, cutting tools wear – especially in mixed ground conditions – and besides disc cutters and/or knife bits, additional tools are needed to encourage muck flow, protect cutterhead structures, and monitor for excessive

Below: Closeup view of disc cutters installed on the cutterhead of one of the Emisor Oriente machines, with carbide bits along the edges of cutterhead spokes





wear.

On the TEO project hydraulic wear detectors have been installed at various locaions and levels, while there is wear detection covering the cutterhead structure throughout the entire face in the form of a wear detection pipe.

Grothen says: "The installation of wear detectors at varying heights on the face of the cutterhead can give warning of excessive wear or of the need to replace cutting tools before damage occurs to the cutterhead structure. Wear detectors use hydraulic pressure that is released when a certain amount of wear occurs and the hydraulic line is sheared, sending a signal to the machine operator.

"Another very important wear detector type is the wear tube. This tube is routed along the surface of the cutterhead structure from the center to the outermost structure, and is protected by the cutterhead wear plate on both sides."

Robbins states that the company invests more on R&D for cutters than any other company in the industry. However, Aaron Shananhan says that improving the overall project through greater wear prediction capabilities could benefit from more research.

Above (left): ***The TBM on the Emisor Oriente project was installed with carbide bits rather than disc cutters***

Above (right): ***Abrasion-resistant wear plating in the form of striations after breakthrough at the San Francisco Central Subway***

"There will always be the potential for incremental improvements in tool performance through the material, processing, and design of tools but I believe that there is greater potential for improving the overall project through greater wear prediction capabilities. Disc cutter wear prediction models are fairly well developed at this point. Soft ground tool wear models take only a few inputs and generate a basic estimate of cutting tool wear. I'm not aware of any predictive model that can accurately predict cutting tool performance in a true mixed face condition."

NEW DEVELOPMENTS

Generally, while some designs for high-pressure cutters used in conditions of plus three bar exist in the industry, their capability is limited in certain conditions. For example, while the standard seal is rated for about three bar of pressure differential between the atmosphere and the bearing cavity, which is reached at 30m below the water table, many tunnels are far deeper.

Various methods have been tried over the years to try to compensate the internal pressure in cutters to match the exterior pressure, in order to overcome the pressure differential problems. "Our approach for handling high pressure situations is to equalise the pressure across the cutter seals so there is no great pressure differential acting against the seals."

"We accomplish this through the use of a patented pressure-compensating device that is compatible with all standard cutter designs. Previous applications of pressure compensation devices in EPB applications have generally not fared well because they utilised small surface area devices that were highly prone to plugging.

"The device has a much greater surface area, requiring very little movement to achieve complete pressure compensation across the seals, negating the need for special high pressure seals"

A TRIBUTE TO MYLES

Myles O'Reilly is retiring as chairman of the *Tunnels and Tunnelling* Editorial Advisory Board (EAB). Holding a seat from the Board's first meeting, Myles was appointed chairman in 1981. In honour of decades of service to the industry, he was awarded the James Clark Medal in 1998. His longstanding colleague and fellow EAB member **Barry New** has written a tribute

Barry New
Barry is an associate of the Geotechnical Consulting Group

MYLES'S GREAT strength has always been as an intuitive engineer with considerable breadth of vision. In 1972 he fitted perfectly into the role as Division Head of the new Tunnels Division at TRRL. Such a position required his drive and leadership skills but paramount was his vision to anticipate and promote the research needs of the industry.

His task as Division Head was to recruit and lead his TRRL team but equally importantly he was to select and sponsor tunnelling research in our higher educational establishments and where appropriate Consultancies. His intuitive ability to promote good proposals and to weed out others was key in this role: Such talents have also been vital as Chairman of the Editorial Board.

In the early 70's the Channel tunnel project was in its infancy and his early work was on pilot scale research into improving efficiency in excavating chalk. This led to the full scale tunnelling trials at Chinnor which provided a wide spectrum of benefits including, improvements in rock cutting, the instrumentation of tunnelling machines, the monitoring of ground movements and improvements in site investigation techniques.

It also provided a rapid 'hands on' tunnelling education and very practical training for his staff. I had just transferred to TRRL from the National Physical Laboratory and working at the Chinnor trials gave me a rapid introduction to tunnelling. I never did get the chalk dust out of my car.

Myles has the ability to pick winners and his early support for Peter Attewell at Durham University and research within TRRL led to the development of a broad empirical and theoretical basis for the prediction of ground movements around tunnels.

His paper, reprinted here, is an example of his foresight in achieving a range of carefully programmed and supervised field measurements on which the predictive model was based and validated.

In some ways not much has changed in respect of the methodology in predicting ground movements around tunnels since the 1982 paper.

That paper introduced the radial flow assumption and the variable trough width parameter formulation which facilitated the application of the Martos/Schmidt/Peck Gaussian assumption to a wide variety of ground conditions and importantly now yielded subsurface movements. The two dimensional model published in the paper also provided ground slope, curvature and strain which are critical in making structural damage assessments. This approach was soon developed into a three dimensional model and relatively minor refinements have been given since.

The paper remains widely cited and, some 33 years after its publication, is still applied throughout the world.

It is perhaps a sad reflection on the failures of the Government to properly support tunnelling research that this remains the case: The continuity provided by Government research is badly missed and a costly loss to UK Ltd.

What has changed dramatically since 1982 is the development of pressurised face TBM's which have reduced ground movements by almost an order of magnitude. Myles's early foresight even extended to supporting the developments in slurry shield technology, firstly at the New Cross trials, and later in 1976 at the first commercial application of the Bentonite shield TBM for the Acton Grange Outfall Sewer in Warrington.

His ability in picking winners extended to his support for Andrew Schofield in the early days of the Cambridge Centrifuge.

The research he chose to sponsor at that time supported several Ph.D. students who today have become world leaders in tunnelling and wider geotechnical research.

Later in his tenure he extended support to soft ground SCL works and the Heathrow Express Trial Tunnel again provided an excellent research platform for his staff who at that time included Keith Bowers who has since gone on to become Head of Tunnel Engineering at London Underground.

Myles's personal talents do not always extend to what he describes as 'suffering fools gladly' and, although rare, his forthright approach to management in difficult situations is well known.

Above all his ability to lead and inspire loyalty in his staff will endure and his oversight will be sorely missed by the British Tunnelling Society's Editorial Advisory Board

SETTLEMENTS ABOVE TUNNELS IN THE UNITED KINGDOM – THEIR MAGNITUDE AND PREDICTION

This paper was first published in 1982 by **Myles O'Reilly** and **Barry New** with conference proceedings printed by the *Institution of Mining and Metallurgy*. Following Myles's retirement from the Advisory Board of *Tunnels and Tunnelling* this month, it is reprinted here in appreciation of his many years of support

SETTLEMENTS CAN be a problem with soft ground tunnelling in urban areas where buildings, both modern and ancient, can be put at risk, services, too, can be endangered and at times it has been deemed necessary to divert services before tunnelling is begun. These environmental considerations have led to a considerable research effort being devoted to the study of settlements caused by tunnelling through soft ground; much of the research work has been undertaken either directly by or under contract for the Transport and Road Research Laboratory. Measurements of settlement and ground movement made on tunnelling projects located, in the main, in built-up areas are reviewed. The ground conditions studied included stiff-fissured clays, glacial deposits and recently deposited silty clays, as well as cohesionless soils of low density, weak rocks and made ground. Many of the tunnels were driven in free air by use of shields, but compressed air was used in the weaker soils to maintain stability; the bentonite shield and chemical treatment of the ground were also used in loose sands. The data from these case studies are used to provide simple analytical tools that enable better prediction of the magnitude of settlements and ground movements caused by tunnelling through soft ground to be made.

One ofthe three basic requirements for the design of a satisfactory tunnel [1] [2] is that its construction should cause as little damage as possible to overlying or adjacent existing structures and services. With soft-ground tunnelling settlement is often a problem in built-up areas, where buildings, old and new, important or otherwise, can be put at risk. Services, too, such as gas and water mains and sewers can be endangered and it has occasionally been deemed prudent to carry out considerable service diversion and relocation works as a prelude to tunnelling.

Myles O'Reilly
Myles, retired, is formerly of the Transport & Road Research Laboratory

To minimise overall project costs and the risk of damage or accident as a result of tunnel construction the engineer who designs the tunnel needs to be able to make reliable predictions of the extent and amount of settlement that are likely to arise from tunnelling in various conditions. Given reliable forecasts of ground deformations he would be in a position to choose between a number of options, that, depending on the particular location, might include:

1. Relocation of the tunnel well clear of sensitive structures
2. A longer tunnel in better ground
3. Chemical stabilisation or freezing of weak ground on the more direct route
4. Underpinning of existing buildings and relocation of water and gas mains

Such considerations and a growing emphasis on environmental problems led to a considerable research effort being devoted during the 1970s, both in the United Kingdom ad abroad, to the study of the settlements and ground deformations caused by driving tunnels in soft ground. Much of this research in the United Kingdom was undertaken either directly by, or under contract for, the Transport and Road Research Laboratory, and the results obtained on some individual schemes and groups of schemes have already been reported [3-13]. At the same time a programme of centrifuge and static model tests was being carried out at Cambridge University to obtain a better understanding of the response of the ground to tunnelling [14-17]. In this paper summarised data from all the tunnel sites studied have been assembled and analysed so that the designers and constructor of tunnels are better equipped to make predictions of the settlements and ground deformations that result from tunnelling.

Barry New
Barry is an associate of the Geotechnical Consulting Group

PATTERN OF GROUND MOVEMENT

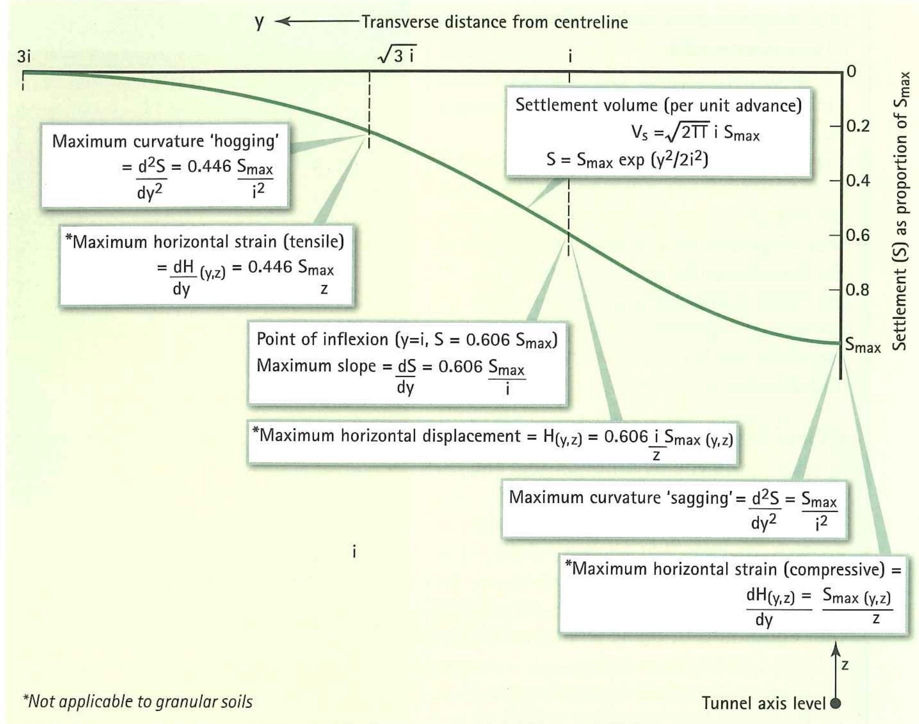
Ground movements above tunnels may conveniently be considered under two headings. The first, surface settlement, may adequately be described by assigning a particular geometrical form to the settlement profile and using case history data to predict its magnitude. Secondly, the horizontal component of surface ground movement and generalised subsurface ground displacements are less easily dealt with, as further assumptions are required to define the nature of the deformations. The lack of reliable case history data – as exist for surface settlements – and the different behaviour of cohesive and cohesionless soils make prediction of these movements somewhat speculative. As surface horizontal and subsurface ground movement will, however, often be of considerable interest, an attempt is made to determine the form of these displacements, particularly in the vicinity of the ground surface.

Surface settlement

Considering only vertical ground displacement at the surface, it is now well established an accepted that the shape of the settlement trough above a tunnel may be reasonably represented by an error function curve of the form:

$$[1] \quad S = S_{max} \exp - \frac{y^2}{2i^2}$$

Where S is the surface settlement at a transverse distance y from the tunnel centre line Smax is the maximum settlement (at y = 0) and i is the standard deviation of the curve. The value of i provides a means of defining the width of the trough and corresponds to the value of y at the point of inflexion of the curve; for practical purposes the width of the trough can be taken as 6i.



Above: ***Figure 1, Settlement semi-profile with error function form***

This formulation was put forward by Martos [18] and was based on statistical evaluation of field observations of settlements above tabular mine openings. Other authors, notably Schmidt [19] and Peck [1], have shown that this approach adequately models the shape of the settlement trough caused by tunnelling in soft ground. On site it is usually more convenient to measure settlement, although it is the angular distortions that result from differential settlement that are of greatest interest with regard to potential damage to overlying structures and installations.

Equations for the ground slope and curvature may be readily derived by differentiation of equation one, and the settlement volume, Vs, per unit advance is obtained by integration:

$$[2] \quad V_s = \int_{-\infty}^{\infty} S\, dy = \int_{-\infty}^{\infty} S_{max} \exp - \frac{y^2}{2i^2 dy}$$

$$= \sqrt{2\pi}\, i\, S_{max} \simeq 2.5\, i\, S_{max}$$

and substituting Smax in equation one gives

$$[3] \quad S = \frac{V_s}{\sqrt{2\pi}\, i} \exp - \frac{y^2}{2i^2}$$

then the slope

$$[4] \quad \frac{dS}{dy} = \frac{-V_s\, y}{\sqrt{2\pi}\, i^3} \exp - \frac{y^2}{2i^2}$$

and the curvature

$$[5] \quad \frac{d^2S}{dy^2} = \frac{V_s}{\sqrt{2\pi}\, i^3} \left[\frac{y^2}{i^2} - 1\right] \exp - \frac{y^2}{2i^2}$$

Given values for Vs and i, these equations may be easily evaluated on a pocket calculator to give the settlement, slope and curvature at any point on the settlement profile. Figure 1 illustrates the form and principal features of this settlement trough.

Horizontal and subsurface displacements

The above description of the shape of the surface settlement trough gives no indication of horizontal ground movement or of the changing width of the subsurface settlement profile as the soil particles migrate toward the area of ground loss in the vicinity of the tunnel. As differing mechanisms are likely to apply, the problem is best considered separately for cohesive or clay soils and for cohesionless sands and gravels.

COHESIVE SOILS

In addition to the assumption that the settlement trough takes the form of an error function curve, the following analysis assumes that all particulate movements in the soil occur along radial paths toward the tunnel axis and that conditions of plane strain constant volume deformation apply.

Support from field measurements for the radial flow postulate is limited by lack of below ground deformation measurements, but the data that do exist do not conflict with such an assumption. The most convincing evidence in support is provided by the results of the centrifuge tests on model tunnels in soft clay reported by Mair [20] (see Figure 2). The information available tends to suggest that the flow is directed towards a 'sink', which is located at a point somewhat below axis level of the tunnel perhaps close to invert level. Such variation in location of the sink is not, however, of significance in consideration of deformations towards the surface well away from the tunnel.

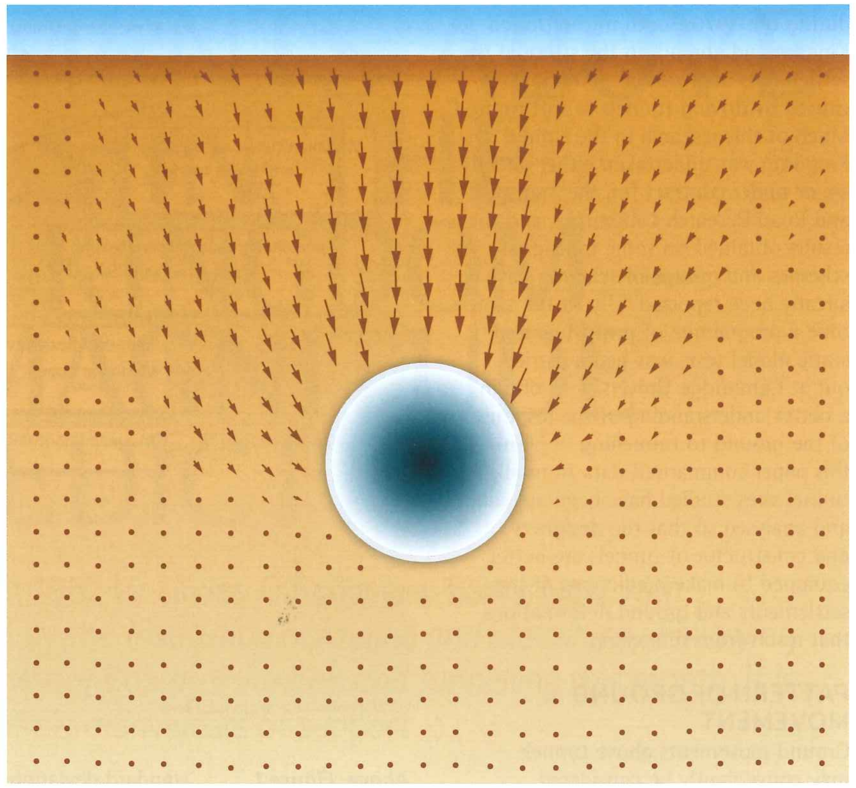
The adoption of radial flow assumption means that the width of the zone of deformed ground decreases linearly with depth below the ground surface. This results in the magnitude of the ground movements increasing linearly with depth below the surface to conform with the plane strain constant volume postulate:

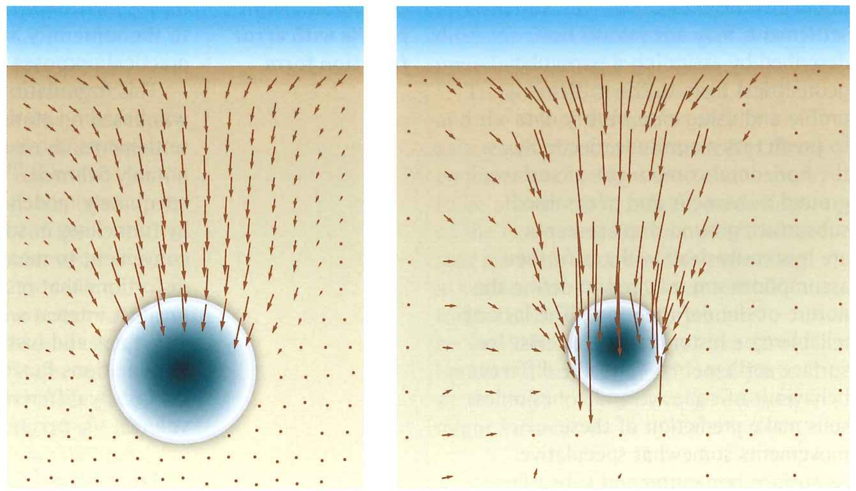
$$[6] \quad i_z = Kz$$

where i_z is the standard deviation (trough width parameter) at height z above tunnel axis and K is an empirical constant of proportionality. It also follows that

$$[7] \quad H_{(y,z)} = \frac{y}{z} S_{(y,z)}$$

where H(y,z) and S(y,z) are, respectively, the horizontal and vertical components of soil displacement at a transverse distance y and a vertical distance z from the tunnel axis. Glossop's [21] stochastic analysis of subsurface movements around tunnels gives a result identical to equation seven, as does Martos [18] for horizontal surface displacements above tubular openings.





Above (top): ***Figure 2, Soil displacements around model tunnel in clay. After Mair [20]***

Above (bottom): ***Figure 3, Soil displacements around model tunnel in sand. (Left: After Potts [22] and Right: After Cording et al [23])***

From equations one, three, six and seven, the generalised displacements are given by

$$[8] \quad S_{(\gamma,z)} = S_{(max,\gamma,z)}\ exp - \frac{\gamma^2}{2i_z{}^2} = \frac{V_s}{\sqrt{2\pi}\ K.z}\ exp - \frac{\gamma^2}{2(Kz)^2}$$

and

$$[9] \quad H_{(\gamma,z)} = \frac{\gamma}{z}\ S_{(max,y,z)}\ exp - \frac{\gamma^2}{2i_z{}^2} = \frac{V_s\,\gamma}{\sqrt{2\pi}\ K.z^2}\ exp - \frac{\gamma^2}{2(Kz)^2}$$

and the vertical and horizontal ground strains (ε_V and ε_H) are:

$$[10] \quad \varepsilon_V = \frac{dS(\gamma,z)}{dz} = \frac{V_s}{\sqrt{2\pi}\ Kz^2}\ exp - \frac{\gamma^2}{2(Kz)^2}\left[\frac{\gamma^2}{(Kz)^2} - 1\right]$$

and

$$[11] \quad \varepsilon_H = \frac{dH(\gamma,z)}{d\gamma} = \frac{V_s}{\sqrt{2\pi}\ Kz^2}\ exp - \frac{\gamma^2}{2(Kz)^2}\left[1 - \frac{\gamma^2}{(Kz)^2}\right]$$

(note that ($\varepsilon_V = -\varepsilon_H$, which satisfies the conditions of plane strain constant volume deformation). These equations are not applicable in the region close to the tunnel – say, within about a diameter of the periphery – because of the simplifying assumptions in their derivation.

GRANULAR SOILS

The analysis given above for cohesive soils is unlikely to be applicable to granular soils as the assumption that particle displacements away from the tunnel are directed toward the tunnel axis is not supported by laboratory studies. Further, the assumption of deformation at constant volume is untenable as some dilation or compaction of granular soils is almost inevitable during deformation. Again, data from the field are limited and inconclusive. Independent model studies reported by Potts [22] and Cording et al [23] indicate a rapid narrowing with large inward displacements of the settlement trough near the ground surface with the sand soils funneling down into the void created by the excavation (see Figure 3). This settlement mode was discussed by Atkinson and coworkers [24] in terms of a dilating wedge over the tunnel crown, which develops until collapse occurs on surfaces that propagate vertically upwards from the tunnel haunches.

This type of ground movement has been noted in the field and, when associated with vertical ground strains in excess of 0.5 per cent, leads to a deep and narrow settlement trough with high horizontal surface strains that may not always be accurately approximated by an error function curve [25].

FIELD MEASUREMENTS

Both the strength of the ground and the method of tunnel construction can affect the distribution and amount of settlement that result from the driving of a tunnel. And, although the grosser effects of soil resistance to deformation at the tunnel collapse condition can be dealt with quantitatively, the construction method adopted and in particular, the rate of advance of the tunnel opening and the application of support can clearly influence the amount of settlement.

The approach adopted in the field investigations was to identify and monitor a number of tunnel construction projects that were located in a range of soft ground formations representative of conditions in the more populous built-up areas of the United Kingdom. Such a collection of case history data would provide, in the first instance, the quantitative information from which estimates might be made on the basis of experience of the likely extent and amount of settlement that result from new tunnelling in similar ground conditions. It would subsequently provide the basic field data on which more rational – less empirical – approaches could be tried and tested.

Stiff fissured clays

The construction of the Victoria Line of the London Underground provided a great deal of data on vertical settlement over tunnels in London Clay during the late 1960s [26]. Further, more detailed studies were carried out at Green Park [3] and Regents Park [5] during the construction of the Jubilee Line, on an access tunnel near Kings Cross Station [13] and on a sewer at Sutton. A comprehensive study of the settlements caused to Grand Buildings during the construction of Strand Station has also been undertaken [27] and, quite recently, measurements have been made over a tunnel driven through Oxford Clay.

Cohesive glacial deposits

Settlement studies have been made at Tyneside on sewer tunnels driven in free air at Hebburn and Howden [25] and at Eldon Square Newcastle on a tunnel that is being driven for the metro.

Recent silty clay deposits

Of considerably more concern are the settlements caused when tunnelling, usually in compressed air, through recent silty clay deposits, which occur widely in coastal areas; their undrained shear strengths are typically in the 10-50kN/m^2 range. Studies in such deposits were first made at Grangemouth, where considerable further settlement was recorded subsequent to the release of compressed air [29]. Further studies have been carried out at Willington Quay [9], at Belfast [10], on the M5 near Bristol [12] and at Grimsby on tunnels driven in compressed air; a small-diameter tunnel driven in free air at Stockton-on-Tees [8] has also been studied.

Cohesionless soils

Traditionally, either compressed air or chemical treatment had been used where required in these conditions to stabilise the tunnel face and control ground movements [30].

The bentonite tunnelling process [31] has recently been developed as an alternative to these and was shown to be effective in controlling ground movements at trials at New Cross [4]. The construction of three lengths of sewer tunnel at Warrington in loose granular soils enabled ground settlements to be monitored where the above three methods have been used as well as on sections of tunnel driven in free air [11]; a hand-excavated tunnel shield driven below the water-table in sand has been monitored at Irvine [32].

Weak rock formations

Settlements have been measured over sections of tunnel driven in chalk at Chinnor [6], in Keuper Marl at Cardiff and in sandstone at Warrington [11].

Loose filled or made ground

Measurements have been made in Newcastle on a sewer tunnel driven across a valley infilled with municipal rubbish; a section of tunnel overlain by fill has also been monitored at Sutton.

Table 1. Settlement data for cohesive soils

Tunnel and source of measurements	Diameter excavated, D, m	Depth to axis, Z, m	Settlement S_{max}, mm	S_{max}/Z, as %	Volume excavated, V_{exc}, m^3/m	Settlement, Vs, m^3/m	V_s/V_{exc}, as %	i,m	Soil properties, Cu, kN/m^2	Excavation method and soil type
NWA Sewerage Scheme, Hebburn [25]	2.01	7.5	7.86	0.1	3.17	0.077	2.42	3.9	73	Hand excavated and lined with concrete segments within shield; laminated clay overlain by stony clay
London Transport Fleet Line (Green Park)[3]	4.15	29.3	6.17	0.02	13.52	0.196	1.4	12.6	270	Hand excavated and lined with cast iron segments; stiff fissured overconsolidated London Clay
London Transport Fleet Line (Regents Park)[5]	4.15 4.15	34 20	5 7	0.015 0.035	13.52 13.52	0.19 0.18	1.4 1.3	15.2 10.3	230 230	Hand excavated and lined with concrete segments within shield; London Clay
Anglian Water Authority Haycroft Relief Sewer	2.7	8	95	1.19	5.72	0.905	15.8	3.8	12 and 100	Hand excavated in shield lined with concrete segments; compressed air applied about 20 days after excavation released about 170 days after excavation; lower 60% of face stiff stone clay, remainder soft marine silty clay (Grimsby Marine Warp) overlain with 2.5m of stiff clay
	(Measurements 375 days after excavation)									
	2.7	5.5	60	1.09	5.73	0.481	1.09	5.73	0.481	Hand-excavated in Grimsby Marine warp overlain with about 1 m of stiff clay; compressed air
	2.7	5.5	58	1.05	5.73	0.407	7.1	2.8	12	
	(300 days after excavation)									
	2.7	6.5	97	1.49	5.73	1.046	18.2	4.3	12	As above; settlement still taking place
	(238 days after excavation)									
Department of Environment for N. Ireland, Sewerage Scheme, Sydenham, Belfast [10]	2.74	4.9	16	0.33	5.9	0.11	1.9	2.7	10	Hand-excavated and lined in shield with concrete segments; compressed air; soft saturated alluvial silt and silty clay (sleech)
	2.74	4.5	20	0.44	5.9	0.12	2	2.4	10	
Tyne and Wear Passenger Transport Executive, running tunnel, Eldon Square, Newcastle	5.21	14.2	7.5	0.053	21.32	0.132	2.42	3.9	73	Partial face machine excavated in shield with compressed air; glacial till; firm/stiff silty clay with some sand and gravel lenses
Thames Water Authority, Sutton sewer	1.78	17.1	3.8	0.022	2.49	0.096	3.86	10	180	Hand-excavated; stiff fissured London Clay
	(16.35)									
	1.78	3.4	3.7	0.109	2.49	0.0186	0.75	2	90	Hand-excavated; firm to stiff weathered London Clay
	(2.65)									
	1.52	4.9	7.1	0.145	1.81	0.054	2.98	3	90	Full-face machine (mini-tunnel) excavated; firm to stiff weathered London Clay
	(4.15)									
Stockton on Tees Borough Council [8]	1.26	6.28	43.7	0.7	1.25	0.38	30.4	3.47	50 (vane)	Hand-excavated and lined (3-segment concrete) within shield (mini-tunnel); soft to very soft silty clay with sand lenses
	1.26	5.86	56.3	0.96	1.25	0.519	41.5	3.68	50 (vane)	
Bristol City Engineers Department Avonmouth Two, Sewerage scheme [12]	3.4	6	20	0.33	9.08	0.251	2.8	5	18	Hand-excavated within shield with compressed air; soft to very soft alluvium overlain with fill for motorway embankment
London Transport interchange subway at Kings Cross, London [13]	4.13	14.06	4	0.03	13.46	0.078	0.6	7.8	230	Hand-excavated (no shield); cast iron lining; London Clay
Thames Water Authority Oxford trunk outfall sewer	2.82	11.7	2.2	0.019	6.24	0.028	0.44	5	200-400	Full-face machine in shield; stiff, heavily overconsolidated fissured clay (Oxford Clay)

Source: Authors

ANALYSIS OF RESULTS

Data from the sites where the settlement profile normal to the direction of tunnelling was established are summarised in Tables One and Two, the former dealing with predominantly cohesive soils and the latter with granular soils; information on the excavation method and ground conditions is also included. It was found that the majority of settlement profiles could, as expected, be represented by an error function curve and values of the trough width parameter, i, and ground loss, Vs, are given for each settlement profile. The simple analysis that follows is designed to provide empirical predictions of i and Vs that together uniquely define the settlement profile.

As had been found previously [19] [33], no well-defined relations were apparent between ground losses and stability ratio [34]. This also proved to be the case when attempts were made to relate ground losses to load factor [17], which, conceptually, has the ability to make allowance for differing ground support conditions at and behind the tunnel face [16] [20] [35].

Difficulties of determining the appropriate value of the undrained shear strength of the ground mass, particularly in stiff fissured clays [36], and uncertainties in the operative P/D ratio (P is the distance from tunnel face to lining and D is excavated diameter of tunnel) values in the field were two reasons for this.

In addition, ground losses are related to the rate of tunnel advance, so in many cases equilibrium will not have been reached by the time that lining is completed.

SETTLEMENT TROUGH WIDTH

The transverse distance from the tunnel centre line to the point of inflexion (y = i) is used to describe the width of the settlement trough and has been considered to be related both to the depth from ground surface to axis, Z, and to a lesser extent the diameter of the tunnel. Multiple linear regression analyses performed on the field data presented here, however, revealed no

Table 2. Settlement data for granular soils and fill

Tunnel	Diameter excavated, D, m	Depth to axis, Z, m	Settlement S_{max}, mm	S_{max}/Z as %	Volume excavated, V_{exc}, m^3/m	Settlement, V_s, m^3/m	V_s/V_{exc}, as %	i, m	Excavation method and soil type
London Transport experimental tunnel (New Cross) [4]	4.15	10	21.5	0.22	13.52	0.135	1	2.5	Bentonite slurry shield; dense sandy gravel overlain with made ground of soft clay with sand and gravel
Ayrshire Joint Drainage Scheme [32]	2.9	6.25	13.5	0.22	6.61	0.048	0.7	1.41	Hand-excavated in shield with compressed air; fine to medium slightly silty sand; loose and medium density
	2.9	6.09	16	0.26	6.61	0.064	1	1.6	
Warrington New Town Development Corporation, Acton Grange Trunk Outfall Sewer [11]	2.87	6.8	19.9	0.29	6.47	0.089	1.37	1.78	Full-face bentonite tunnelling machine; concrete segment lining inside shield; fine to medium fairly loose blown sands; occasional gravel and erratic cobbles
	2.87	6.8	19.9	0.29	6.47	0.071	1.1	1.99	
	2.87	6.8	14.2	0.21	6.47	0.118	1.83	1.12	
	2.87	6	42.2	0.7	6.47	0.083	1.28	1.78	
	2.87	6	18.6	0.31	6.47	0.99	1.53	1.56	
	2.87	5.8	25.3	0.44	6.47	0.021	0.33	3.81	Fully stabilised sands and gravel
WNTDC Lumb Brook Sewer [11]	3.6	4.7	78	1.7	10.18	0.47	4.6	2.4	Hand-excavated within shield; loose to medium sand with some gravel
	3.6	9	19	0.21	10.18	0.12	1.2	2.52	Hand-excavated in medium to dense sand with some clay; cover of very stiff sandy clay
	3.6	6.5	15	0.23	10.18	0.06	0.6	1.59	Partially stabilised medium/dense sands and gravel with a little clay
	3.6	6.5	20	0.31	10.18	0.09	0.9	1.79	
	3.6	6.5	7	0.11	10.18	0.04	0.4	2.28	Fully stabilised sand and gravel
North West Water Authority, Mersey Street to Howley Sewer [11]	2	8.4	28	0.33	3.14	0.23	7.1	3.2	Hand-excavated within shield with compressed air; variable loose silty sand with some soft clay; tunnelling about 4m below water table
Northumbrian Water Authority Sewerage Scheme, Ouseburn Valley	3.47	13	81	0.623	9.46	1.48	15.6	7.29	Hand-excavated within shield; recent fill materials, rubble, timber, household waste and ash in soft silty clay matrix

Source: Authors

significant correlation between the trough width parameter, i, and tunnel diameter, although the expected strong correlation of i with tunnel depth, Z, was found. This was true for both cohesive and granular data groupings. This finding is to some extent explained by Glossop, who carried out an analysis based on stochastic/numerical modelling techniques [21]. The analysis showed that at distances of more than about one tunnel diameter from the periphery of the tunnel the shape of the settlement trough is not significantly dependent on the tunnel diameter and the loss of ground may be considered to occur at a point 'sink' located at the tunnel axis.

The two-variable regression analyses carried out on the data in Table One and Two gave the relationships:

[12] $i = 0.43Z + 1.1 \; (r^2 = 0.96)$
for cohesive soils

and

[13] $i = 0.28Z - 0.1 \; (r^2 = 0.78)$
for granular soils

where i and Z are in metres.

Figure 4 shows the trough width parameter plotted against tunnel axis depth for both ground types. The linear relationship for cohesive soils is well defined.

The fewer data for granular soils are more scattered and reflect the often unpredictable consequences of tunnelling in such ground. The data do not suggest that any relationship between i and Z, other than linear, would be more appropriate for either ground conditions.

The linear regression lines pass close to the origin and may for most practical purposes be simplified to the form

[14] $i = KZ$

where K = 0.5 for cohesive or 0.25 for granular soils. Further review of field data suggests that for clays K varies between 0.4 (stiff clays) and 0.7 (soft, silty clay). For granular materials above the water-table K ranges between 0.2 and 0.3.

VOLUME OF LOST GROUND

As has already been discussed, both ground conditions and construction method determine the ground losses that result from tunnelling. To normalise the volume of lost ground with respect to tunnel size the volume of the settlement trough at the surface, Vs, is expressed as a percentage of the tunnel volume excavated, Vexc.

Examination of Tables One and Two shows that the volume of lost ground is well related to ground conditions. In the stiff fissured London Clay ground losses for the 4m-diameter underground railway tunnels fall in the 1-2 per cent range. Ground losses can be somewhat larger on the smaller tunnels, where the overcut annulus around the shield represents a larger proportion of the excavated cross-section; on the other hand, losses may well double over a station complex with large multiple openings [27]. Ground losses were 0.4 per cent over a 2.8m-diameter sewer tunnel in Oxford Clay.

Although there are only two examples, the volume of lost ground for tunnels driven in free air in cohesive glacial deposits appears to be marginally higher, up to 2.5 per cent, than is found in London Clay. The application of compressed air has reduced total ground losses to 1.25 per cent, of which 1 per cent had occurred by the time the compressed air was released.

Settlement occurs at tunnels driven through soft recent silty clay deposits in two distinct parts: (1) an initial portion that, as for tunnels driven in free air, commences as the tunnel approaches the measurement point and, finally, stabilises sometime after the tunnel has gone past and (2) a second phase that commences with the release of air pressure and continues often for considerable periods thereafter. The amount and extent of the settlement during the second phase may well exceed that in the initial phase and has on occasion caused considerable damage to overlying buildings, e.g. at Willington Quay the volume of ground lost was 2.6 per cent and 10.5 per cent of the tunnel volume in the initial and second phase, respectively. Ground losses of 32-42 per cent were recorded during the driving of the small-diameter tunnel at Stockton-on-Tees in such soils.

In the cohesionless soils at

Table 3. Summarised settlement data for cohesive soils

Ground conditions	Ground support method in tunnels	Trough width parameter constant, K	Ground loss Vs/Vexc, %	Remarks
Stiff fissured clay	Shield or none	0.4-0.5	0.5-3	Considerable data available; losses normally 1-2%
Glacial deposits	Shield in free air	0.5-0.6	2-2.5	
	Shield in compressed air		1-1.25	Compressed air used to control ground movements
Recent silty clay deposits (Cu = 10 - 40kNm2)	Shield in free air	0.6-0.7	30-45	Failure or near-failure conditions usual
	Shield in compressed air		5-20	Some partial face values included

Source: Authors

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Warrington ground loss was about 7 per cent in the tunnel driven below the water table in loose sand with Standard Penetration Test (SPT) values of 2-8, and in a tunnel driven nearby in loose gravels, following groundwater lowering, losses were 4.5 per cent. Where the bentonite tunnelling process was used ground losses were usually less than 2 per cent. On the sections of tunnel where chemical treatment was used, ground losses did not, in general, exceed 0.5 per cent, although quite damaging ground movements were caused when the chemicals were being injected from the ground surface.

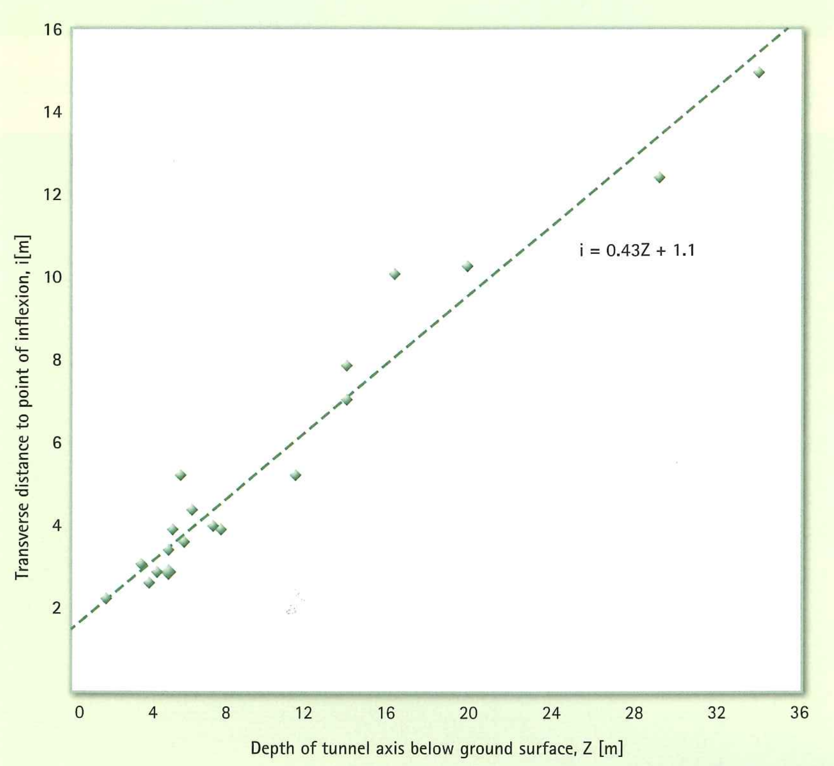
Ground losses above a tunnel driven through municipal rubbish were 16 per cent, and at Sutton the volume of the settlement trough was more than doubled where the in-situ London Clay was overlain by backfilled ground. In weak sandstone [11] and in chalk [6] the volume of lost ground was similar to that found on chemically treated sands, and no movements were detected at the ground surface over a tunnel driven at depth in Keuper Marl in Cardiff.

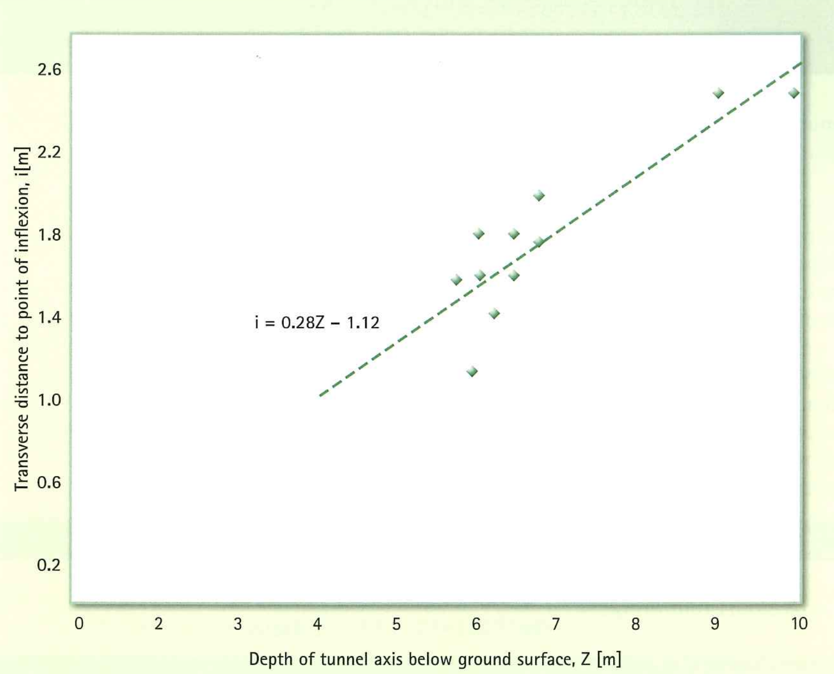
PREDICTION OF GROUND DISPLACEMENTS

Predictions of ground displacements may be made by substituting the appropriate values of i and Vs by use of the information discussed earlier into the appropriate equations given in the section 'Pattern of ground movement'. The value of i may be taken from equation 14 or, where possible, related more specifically to ground conditions on site. The estimate of settlement trough volume may be based on values given in the section 'Volume of lost ground' and should, where possible, include an engineering appraisal that takes account of the proposed tunnelling methods and site conditions and peculiarities.

The data obtained on cohesive soils can be summarised as shown in Table 3; the values of the trough width parameter constant, K, for the recent silty clay soils allows for a considerable amount of long-term settlement, but some further movement may still take place. The results for granular soils are fewer and more variable and, as yet, there are no marked trends.

Given the uncertainty involved, calculations for design purposes should check the sensitivity of the situation to the likely range of conditions to be encountered. Estimates of the 'best' and 'worst' cases should be made to bracket the extent and depth of ground deformation – this provides a useful starting point in any assessment. It is important to realise that this predictive model can only give a general indication of the form and magnitude of the prospective settlement. In practice, unexpected ground conditions on site or difficulties of construction or poor tunnelling technique or a combination of all three could lead to significantly different ground displacements. The values suggested for i and Vs are derived from data limited as follows:





***Above:* Figure 4, Variation of trough width parameter, i, with tunnel depth. Top: Cohesive soils; Bottom: Granular soils**

A. Tunnels with a cover of at least one diameter
B. Tunnel diameters 1-5m approximately
C. Maximum depth to axis, Z of 10m for granular materials
D. Maximum depth to axis, Z of 30m for cohesive materials

Strictly, therefore, they are only applicable within these limits, but the indications are that the values would not be appreciably different for reasonable extrapolation beyond the limits of 'B', 'C' and 'D' above, but the limitation on cover must not be contravened. Further, the analysis given is two-dimensional

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and, although this may be satisfactory in the prediction of conditions subsequent to the tunnel construction, other significant ground deformations of a three-dimensional character may occur during the passing of the tunnel face [16] [20] [35]. Considerable monitoring of ground and building settlement is now routinely carried out on most tunnelling projects in urban areas. Where the extent and/or magnitude of the predicted settlement are important, consideration should be given to arranging the construction programme so that the settlement profile is determined in a 'safe' location, e.g. under parkland, as early as possible in the project.

Such data interpreted within the framework given here enable the predictions made during the design stages to be revised so that decisions on costly underpinning or ground treatment can be made on the best available information.

CONCLUSION

The researches of the past decade have greatly improved the understanding of the settlement of the ground that results from tunnelling, and the designers and constructors of tunnels are today in a much better position to estimate and to some extent control such ground movements. Considerable gaps in knowledge remain, however, and the amount of usable field data is still quite limited; this is particularly so for subsurface deformations, especially close to the tunnel periphery, where any non-uniformity or asymmetry in the situation can be magnified and exaggerated.

Clients, consulting engineers and contractors could do much to add to the store of knowledge; in many cases this would only involve marginal extensions to settlement monitoring programmes that are already undertaken. In the past data collected on ground settlements has often been less than comprehensive.

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In many instances settlements above the tunnel centre line only were obtained, so the lateral extent of the disturbance and the distortions in the ground cannot be determined.

The minimum requirements for settlement data to be suitable for analysis are:

1. Complete definition of the settlement trough – this requires measurements of settlement to be made to a distance of 1.5 to 2.5 times the depth of the tunnel from centre line
2. Information on ground conditions, including water table levels and some indication of soil consistency, such as undrained shear strength or SPT
3. Details of tunnel size, depth, method of construction and lining

The ground deformations due to tunnelling having been estimated, their effect on nearby structures and services has to be assessed. The interactions between ground and structures can be extremely complex and only broad-brush treatments are currently available to tackle the problem [37] [38]. The problem is inherently less difficult for services and the situation is further improved by research into the effects of nearby excavations on them [28] [39] [40]

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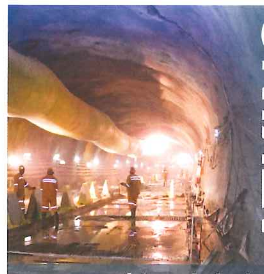
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ISRM Congress 2015
10-13 May 2015
Montreal, Quebec
Held in conjunction with the CIM Convention for 2015, the International Symposium on Rock Mechanics holds its international conference every four years. There will be a one-day symposium on "Shale and Rock Mechanics as Applied to Slopes, Tunnels, Mines and Hydrocarbon Extraction" (ARMA & CARMA Initiative), Chaired by Herbert Einstein of MIT.
www.ISRM2015.com

World Tunnel Congress 2015
22-28 May 2015
Dubrovnik, Croatia
WTC 2015 heads to Croatia as the annual event returns to Europe. The motto of the conference is 'Promoting Tunnelling in the South East Europe Region'. The organisers have said that they hope for a sharing of international experience with local groups.
www.wtc15.com

RETC
7-10 June 2015
New Orleans, USA
The biennel conferece will be held at the Sheraton Hotel in New Orleans, Louisiana this year. The organisers have announced that the 2015 show should be as successful as the 2013 event which had the largest number of attendees, exhibitors and papers in the show's history.
www.retc.org

49th US Rock Mechanics / Geomechanics Symposium
28 June-1 July 2015
San Francisco, California
The 2015 program will focus on new and exciting advances in rock mechanics and geomechanics and encompasses all aspects of rock mechanics, rock engineering, and geomechanics.
www.armasymposium.org/

Tunnel Expo Turkey
27-29 August 2015
Istanbul, Turkey
Turkey is fast growing in the tunneling sector. This event namely Tunnel Expo Turkey focuses on the fast growth.
www.10times.com/tunnel-expo-turkey

Crossrail's tunnelling story exhibit - final day
31 August 2015
London, UK
The final day of the six-month exhibit on Crossrail at the London Transport Museum in Covent Garden. It's open seven days a week for the majority of the day, don't miss out.
www.ltmuseum.co.uk

Bauma Conexpo Africa 2015
15-18 September 2015
Johannesburg, South Africa
The premiere of bauma Africa in September 2013 attracted 754 exhibitors from 38 countries and 14,700 visitors from over 100 countries. Covering a total of 60,000sq.m of exhibition space, this is the biggest event for the sector in Africa.
www.bcafrica.com

Roads. Bridges. Tunnels International Exhibition
23-25 September 2015
St. Petersburg, Russia
Roads. Bridges. Tunnels (the International Specialised Exhibition) takes place in St. Petersburg, Russia from 23 September to 25 September. The trade show is organised by Restec.
www.tofairs.com

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www.icuee.com

Workshop on Innovations and Challenges in Tunnelling
5-6 October 2015
Kingston, Ontario
Save the date for the TAC 2015 Workshop, AGM and annual awards dinner, to be held at Queen's University's Grant Hall in Kingston. Further details of the workshop including program and registration will be available in Summer 2015.
www.tunnelcanada.ca

Eurock 2015 & 64th Geomechanics Colloquium
7-10 October 2015
Salzburg, Austria
The ISRM Regional Symposium EUROCK 2015 Future Development of Rock Mechanics, is to be held in conjunction with the 64th annual Geomechanics Colloquium also in Salzburg.
www.eurock2015.com

25th World Road Congress
2-6 November 2015
Seoul, South Korea
The World Road Congress has been held every four years for more than 100 years. Since the first meeting in Paris in 1908, it has toured the member countries of the non-government organization, Permanent International Association of Road Congresses (PIARC).
www.aipcrseoul2015.org

ITA Tunnel Awards
19 November 2015
Hagerbach, Switzerland
The International Tunnelling Association has launched its own independent awards to recognise industry achievements. The first presentation will be held alongside a conference and banquet at the Hagerbach Test Gallery.
www.awards.ita_aites.org

Third Arabian Tunnelling Conference and Exhibition
23-25 November 2015
Dubai, UAE
This conference is the industry's opportunity to share the knowledge, projects and application experiences, and provide you the opportunity to hear what others have to say. Case studies, which show real-world applications and the implementation of new technologies.
www.atcita.com

Stuva Conference
1-3 December 2015
Dortmund, Germany
Held every two years, this conference sees 1,500 participants and visitors from about 20 countries. It is numbered among the world's leading get-togethers for underground construction experts. In 2015 the chosen venue for this premier event is Dortmund.
www.stuva-conference.com

Building simulation
7-9 December 2015
Hyderabad, India
This conference is the 14th International Conference of the International Building Performance Simulation Association.
www.bs2015.in

2016

International Symposium on Tunnel Safety and Security
16-18 March 2016
Montreal, Canada
Tunnel safety and security is a challenge for both private and public sectors. ISTSS provides a forum to discuss current practice and emerging trends and research in the field of tunnel safety and security. Each day will be opened by invited Keynote Speakers.
www.istss.se/en

NASTT's No Dig Show
20-24 March 2016
Dallas, USA
The overall No-Dig Show program is focused on one objective: helping you maximize your investment in trenchless technologies, services and applications. Owners, utilities and municipalities can immediately benefit.
www.nodigshow.com

Bauma 2016
11-17 April 2016
Munich, Germany
The 31st meeting of the world's largest trade fair for construction machinery, building material machines, mining machines, construction vehicles and construction equipment.
www.bauma.de/en

World Tunnel Congress and North American Tunnelling conference 2016
June 2016
San Francisco, California
The 2016 World Tunnel Congress (WTC) and the 39th General Assembly of the International Tunnelling and Underground Space Association (ITA) will be held in conjunction with the UCA's North American Tunneling conference. Bringing the three events together in the US is unprecendented.
www.smenet.org
www.wtc2016.us

GeoChina International Conference
25-27 July 2016
Shandong, China
This conference will provide a showcase for recent developments and advancements in design, construction, and safety Inspections of transportation Infrastructures and offer a forum to discuss and debate future directions for the 21st century. Conference topics will cover a broad array of issues
www.geochina2016.geoconf.org

British Tunnelling Society

The BTS has a membership of almost 700 individual and 60 corporate members. It is one of the most vibrant gatherings of professional tunnellers in the world and traces its history back to its founding in 1971. Regular BTS monthly meetings are hosted at the Institution of Civil Engineers in London from 5.30pm every third Thursday of the month.

BTS Annual Dinner
8 May 2015
The BTS Annual Dinner will be held at the now traditional Brewery venue at 52 Chiswell Street in Central London. The event starts at 7.00pm and runs until1.00am. Booking is now closed, although John Scholey can be contacted in case of cancellations.

BTS Annual General Meeting and East Side Access project presentation
21 May 2015
The East Side Access Project in New York is the first expansion of commuter rail in New York in over 100 years. When complete it will provide a direct link for Long Island Rail Road commuters to a new terminal beneath the existing 100 year old Grand Central Terminal on the east side of Manhattan.
Speaker: Andy Tompson

Tunnelling in the Lambeth Group: how can we stop it going wrong?
18 June 2015
A presentation by a leading geologist with expertise in the interpretation of complex soils and rocks as well as the geology of London and Southeast England.
Speaker: Jackie Skipper

BTSYM presentation: Fastenings in tunnels
25 June 2015
A presentation by speakers from specialist design company Dr. Sauer & Partners and supplier Fischer Fixings. The two speakers have in previous years hosted succesful workshop sessions on this subject.
Speakers: Panos Spyridis and Mirka Valovicova

BTS Design and Construction Course
29 June - 3 July 2015
The five-day annual BTS Tunnel Design and Construction Course aims to provide a comprehensive introduction to all aspects of tunnelling. The course speakers are all recognised industry experts in their own fields and drawn from the BTS. Five BTS-sponsored spaces are available.

Innovation and technology in segmental lining design
17 September 2015
A presentation by a tunnel engineer who has extensively published on topics related to segmental lining solutions.
Speaker: Anthony Harding

Waterview Connection project in Auckland, New Zealand
15 October 2015
The Waterview Connection project is New Zealand's largest and most complex roading project. It is due to be completed by 2017, and includes one of the country's most challenging tunnels to-date: 2.4km of 14.1m-diameter twin bores.
Speaker: Chris Ashton

If you have a topic or project you feel would be suitable for a BTS evening presentation, please contact:

Greg James: greg.james@ice.co.uk
Dave Terry: david.terry@lbassoc.co.uk

See the society website for further information: www.britishtunnelling.org.uk

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