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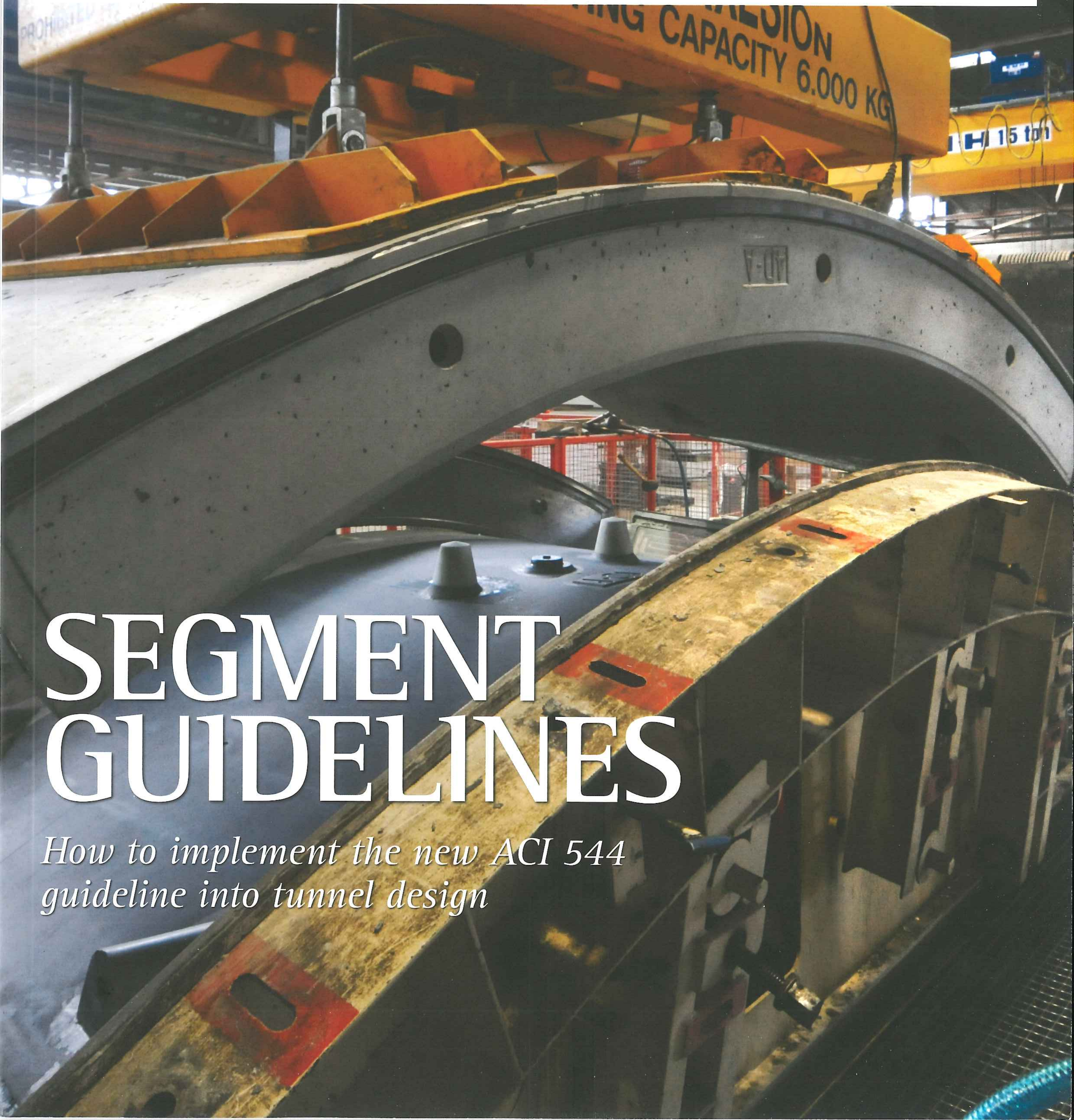
Tunnels AND TUNNELLING



SEGMENT GUIDELINES

How to implement the new ACI 544 guideline into tunnel design

PRODUCTIVITY PROBLEM

Alex Conacher
The *Tunnels and Tunnelling* editor has been with the magazine since 2010

The ITA Executive Committee met in the London last month. Taking the opportunity to attend the September BTS meeting, ITA president Tarcisio Celestino was invited to say a few words to the assembled engineers ahead of the scheduled lecture by high speed rail technology in China.

During his address, Celestino spoke about a recent article in the Economist magazine that took aim at the global construction industry for a perceived lack of productivity.

The article, published online on 17 August 2017, calls construction the worst-performing out of all industries. Using the McKinsey consultancy as its source, it says things are particularly bad in rich countries. Since 1995 it claims, France and Italy have seen a reduction in productivity by 17%, Germany and Japan are flat, while the US has endured a 50% plunge.

With construction at 13% of global output, if its productivity growth had matched manufacturing, the world would be USD 1.6 trillion better off per year.

Construction of course has a major difference with manufacturing that Celestino raises: that construction does not take place in the perfectly sanitised and controlled environment of a factory. There are unexpected site conditions to contend with and interactions with third parties. No two jobs are alike, even in construction sectors more predictable than tunnelling and underground construction.

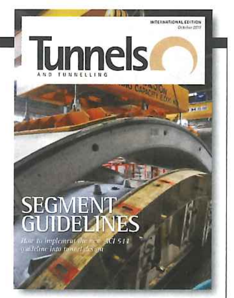
The article from the Economist does not mention this, but it does throw out some other interesting points that it suggests to be the cause:

- In America, fewer than 5% of builders work for construction firms that employ over 10,000 workers, compared with 23% for business services and 25% for manufacturing
- Profit margins are lower than any industry besides retail
- The highly cyclical nature of the business (boom-bust investment)

A couple of solutions are touted out: government efforts to smooth the investment rollercoaster and requirements for firms to implement new technologies (i.e. BIM) to bring the industry up to date.

Should we assume, in the case of tunnelling in particular, that a straight productivity measurement (cost of input vs value of output) is a valid indicator of the industry's success? Particularly given the dramatically increasing complexity of work. If so, what are the chances or means of resolving such a problem? Thoughts on a postcard: editor@tunnelsandtunnelling.com

Cover
This issue's front cover is from the article on the design considerations for the new ACI 544 guidelines.



Next issue
In the next issue of *Tunnels and Tunnelling International* we have a special focus on geotechnical risk in tunnelling projects, with articles covering the role of the ground model, site investigation, the evolution of software and more.

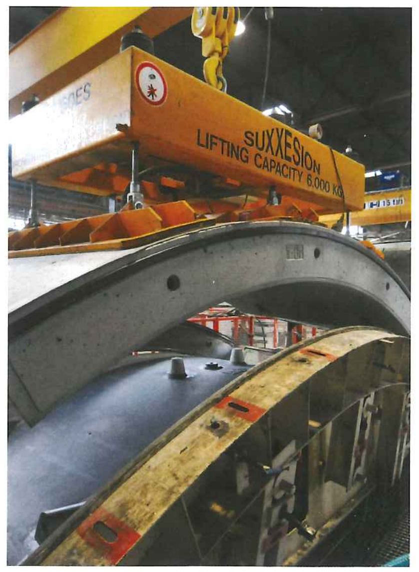
This month...

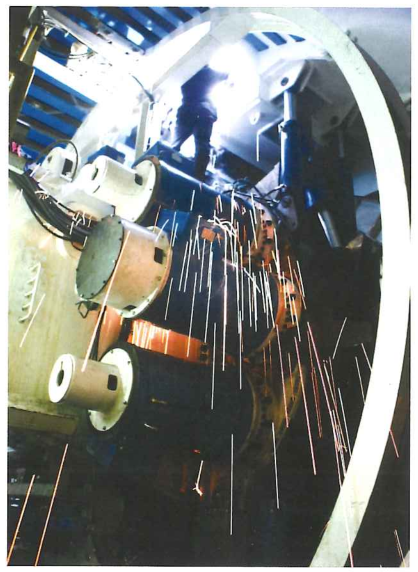
30 YEARS AGO
After six years of open-cut construction, work on the Cairo Metro is now inaugurated. On 27 September 1987, President Hosni Mubarak of Egypt and Prime Minister Jacques Chirac of France officially opened the first phase of the underground network built with substantial financial, design and construction input from the French. The first phase is the 4.7km central underground section with one surface and five underground stations which links the Helwan and El Marg regional railway lines.
Tunnels and Tunnelling, October 1987, p.11

40 YEARS AGO
A 150m-long tunnel, cut to a nominal 2x2m has recently been developed at a depth of 3,090m below the surface at ERPM Gold Mine on the East Rand, South Africa. The tunnel is intended purely for research and its purpose is two-fold. Firstly it provides access to a region of the rock mass where it is expected that rockbursts will occur as stoping approaches ever closer to the tunnel. It will thus be possible to instrument the tunnel and carry out fundamental research on the rock burst problem. Secondly the tunnel is to be used as a proving ground for various types of tunnel support. Some of the support systems are in current use while others have not yet been installed in gold mine tunnels. The rock mass throughout the tunnel is a hard, strong quartzite.
Tunnels and Tunnelling, September/October 1977, p.23


page 19


page 24


page 33


page 41

CONSTRUCTION STARTS ON DELAWARE AQUEDUCT BYPASS TUNNEL

USA — The New York City Department of Environmental Protection (DEP) held a ceremony on 8 September to mark the start of tunnelling for the Delaware Aqueduct Bypass Tunnel.

The USD 1bn project is the largest repair in the 175-year history of the city's drinking water supply. The project will repair two areas of leakage within the 85-mile Delaware Aqueduct, the longest tunnel in the world, DEP said. The primary leak will be eliminated through the construction of a 2.5-mile (4km-) bypass tunnel, which will be drilled 600ft (182.8m) below the Hudson River from Newburgh to Wappinger.

Contractor Kiewit-Shea Constructors (KSC) is deploying a Robbins single shield TBM, 6.8m in diameter. The machine is built to withstand 30 bar of pressure—believed to be the most of any TBM ever manufactured, DEP said.

The machine needs to withstand that much pressure because workers encountered huge inflows of water under immense head pressure when the aqueduct was first built more than 70 years ago.

The TBM is also equipped with dewatering equipment to pump 2,500 gallons per minute away from the tunnel as the machine pushes forward. In addition, the machine is outfitted with equipment to install and grout the concrete lining of the tunnel, and to convey pulverized rock to a system of railroad cars that will follow the TBM as it works.

Once the TBM begins its work, DEP expects it will drive about 50ft (15.2m) of tunnel per day. Work on the tunnel will continue 24 hours a day, five days a week. Tunnelling is expected to take 20 months.

Tunnel diameter will measure 14ft (4.2m) with a steel liner and a second layer of concrete. Once finished the tunnel will be connected to structurally sound portions of the existing Delaware Aqueduct to convey water around the leaking section—an approximately six-month-long shutdown planned for October 2022. The leaking stretch will be plugged and permanently taken out of service.

Over the past several months, workers have already blasted 130 linear feet of starter tunnel, and as of late September workers in Newburgh began to lower the USD 30M TBM into the launch chamber, 845ft (257m) below the ground.

The machine is currently being stored in 22 pieces. It will take workers approximately four months to assemble the TBM.

Top and above left: *An event on 8 September celebrated the start of the TBM's assembly*
Above right: *DEP acting commissioner Vincent Sapienza*
IMAGES COURTESY OF NYC DEP

Cross River Rail to partner with industry

AUSTRALIA — The Cross River Rail will be a public private partnership (PPP) and the Cross River Rail Delivery Authority announced that it is looking to link with the private sector to deliver core components of the project. The decision was presented to 500 'industry leaders' at a briefing on 30 August.

Registrations for the Tunnel, Stations and Development PPP Expression of Interest (EOI) opened on 5 September on the QTenders website (www.hpw.qld.gov.au/qtenders), and registrations for the Rail, Integration and Systems Alliance EOI opened on 19 September.

Materials from the industry briefing can be found through the following link: https://www.crossriverrail.qld.gov.au/cross-river-rail-industry-information/

Two more TBMs manufactured for Mumbai

INDIA — The first of two slurry machines destined for the UGC03 contract of Mumbai Metro Line Three underwent factory acceptance in September.

The 6.65m-diameter Robbins machines will be operated by a joint venture of Dogus and Soma to bore parallel 3.5km tunnels. The alignment will pass through three cut and cover stations along the way.

Ground conditions will consist of fresh to weathered basalt and breccia up to 100MPa UCS, with water pressure up to 3 bar.

According to the contractor, slurry will suit the variable but hard rock local ground conditions. The 17" cutters will be fitted with wear protection, and wear detection bits. Grizzly bars will put a 250mm limit on boulders entering the cutterhead.

The line is expected to be operational by 2021.

AKRON TBM HONOURED WITH LAGER

USA — Few if any in the tunnelling industry will turn down a beer, and in a fitting tribute an Akron craft brewery developed a cold one to commemorate the TBM starting work on the city's 1.9km Ohio Canal Interceptor Tunnel.

Launched in August for the ceremonial christening of the 9.26m diameter TBM, Thirsty Dog Brewing Co. created "Rosie Digs," a Helles lager, 4.8 per cent alcohol by volume on a limited production run.

The Robbins Crossover machine has been named "Rosie" after Rose May Jacob, an Akron native who worked at an aircraft manufacturing plant during WWII—often referred to locally as Akron's own Rosie the Riveter, the era's cultural icon pictured on the label.

Cowi to design Fornebu Line

NORWAY — A Cowi-Multiconsult joint venture has been selected to design an 8.5km extension of the Oslo Metro. The new line will connect the Fornebu peninsula to the capital and is Oslo's largest transport project for 20 years.

The new metro line will run underground from Oslo's transport hub, Majorstuen, west to Fornebu - a peninsula that was formerly the site of Oslo's international airport and has since been redeveloped into a mixed residential and business district.

The Norwegian Government's latest National Transport Plan calls for construction of the new line to begin in 2021 and complete in 2025.

Above: Artist's concept of a new Oslo station

DTSS awards Phase 2 tunnel contract

SINGAPORE — Zublin announced in September that it had been hired by PUB, Singapore's national water agency, to build 11.9km of tunnels for the sewerage system of the city. The contract is a part of the Deep Tunnel Sewerage System (DTSS) Phase 2 project and worth EUR 309M (USD 370M).

The contractor said construction is scheduled to start in March 2018 and will be finished in September 2023. Four TBMs will be used to excavate the tunnels ranging in diameters between 3.5m to 6m.

The DTSS is a systems of deep tunnel sewers conveying waste water by gravity to centralised water treatment plants, where the waste water is cleaned. The whole DTSS project is divided into two phases. Phase one was completed in 2008, where Zublin successfully constructed one section of the project. Phase two will be completed in 2025. Upon completion, Singapore will have an additional conveyance system that is made up of 60km of link sewers and 40km of deep tunnels.

Ontario culvert twinned

CANADA — CRS Tunnelling announced on 11 September that it has completed a 61m, 1,800mm RCP culvert to twin an existing, like diameter culvert under Highway 400 in Barrie, Ontario, for the Ontario Ministry of Transportation. Crews installed the culvert with an Akkerman Series II 720 TBM and tunnel boring system in under a week's time. The ground conditions were compacted sand and sandy clay.

CBE CELEBRATES 500 PROJECTS

FRANCE — Tunnel segment mould manufacturer CBE has taken on its 500th project. The milestone happened to fall in the group's 30th anniversary, which it has been celebrating this year.

The project is the Paris Line 15 South, part of the Grand Paris Express project and comprises two tunnels, one running for 4,679m and one for 2,159m. CBE will supply a carousel and six sets of moulds. Segment production was due to begin in September as *Tunnels and Tunnelling* went to press.

Didier Lefebvre, CEO of the company said, "We are marking history twice with these 500 tunnel projects achieved worldwide with our moulds. [...] The fact that this 500th project takes place in France is highly symbolic and can be seen as a nod to our history. Our teams are all very proud of the work accomplished through the years."

The system itself is a modular carousel, fitted with a new heating system (air heating rather than heat generated in the more traditional way, passing a current through a resistive material) that saves energy by recovering the heated air. There is also a water spraying system to regulate humidity in the curing chamber.

A spokesperson for CBE added: "The production line has also gained a few novelties: a reinforced camera system on the transfer gantry and flying bucket has been added, as well as an automated stacker designed to simplify stacking between the tilting device and the pre-storage phase.

"A pre-storage carousel completes those innovations: it allows segments to cool down progressively before stocking them outside."



Above left: The SR99 project Centre: A casting yard in Beijing Above right: Demoulding segments for the Follo Line

Corrib tunnel contractor fined for fatality

IRELAND — Wayss & Freytag has been fined following a guilty plea to a health and safety incident that caused the death of a worker on the 4.9km Corrib Gas Tunnel project.

The EUR 300,000 (USD 354,500) penalty was due to an offence under Section 12 of the Safety, Health and Welfare at Work Act 2005, contrary to Section 77(2) and Regulation 31(b) of the Safety, Health and Welfare at Work (General Application) Regulations, 2007.

According to the Ireland's Health and Safety Authority (HSA) on the 8 September 2013 Lars Wagner, an employee of Herrenknecht, received fatal head injuries when a pipe he was working under collapsed on top of him as a result of an over pressure event in that pipe system.

The accident occurred in the gear chamber of a TBM that was constructing the tunnel. Wagner was engaged in maintenance activity at the time of the accident.

The TBM was in operation while Wagner was in the gear chamber, contrary to the manual that stated that maintenance work should only be carried out on a stopped TBM.

Brian Higgisson, assistant chief executive of the HSA said: "Maintenance operations can be dangerous and should always take place in a planned and controlled manner.

"The most important consideration is to make sure that work does not place anyone in danger, in this case the failure to follow safety procedures led to tragedy."

Aurecon appoints infrastructure chief

INTERNATIONAL — Aurecon has appointed Ben Stapleton as its managing director for infrastructure.

The company said Stapleton has experience as a leader and advisor in the infrastructure industry across many geographies and roles that will assist clients navigate mounting complexities, including changing funding mechanisms and delivery models.

Global CEO Giam Swiegers says Stapleton brings strong leadership and advisory capabilities to major growth markets. He added: "Stapleton will play an important role in contributing subject matter expertise to clients working in a complex global environment, who need asset optimisation, support with digitisation and smart infrastructure solutions."

Above: Ben Stapleton

TUNNELS AND TUNNELLING PROJECT LISTINGS 2017

The *Tunnels and Tunnelling* Annual Listings is introducing an improved format. This year in addition to the usual corporate details, companies have the opportunity to list sample projects showcasing their expertise and innovation in a practical way.

Users can detail products or services supplied to up to three jobs (depending on the listing type selected on the first page) and describe the challenges they helped to overcome.

Please use the navigate to the page below to fill out an entry for your company. We will be accepting submissions until 1 November, but no later.

http://www.tunnelsonline.info/news/tunnels-and-tunnelling-project-listings-2017-5902056/

BTS HEALTH AND SAFETY COURSE

Above: The course will teach health and safety best practice

GREAT BRITAIN — The British Tunnelling Society (BTS) is accepting registrations for its health and safety course.

This year the event takes place on Monday 27 and Tuesday 28 November.

The Health & Safety Course is organised and run by the British Tunnelling Society (BTS), an Associated Society of the Institution of Civil Engineers. The purpose of the course is to provide a comprehensive introduction to health and safety in tunnelling.

The course has been developed to focus exclusively on the underground environment. It aims to provide an introduction or enhance existing basic knowledge and develop an awareness of the particular health and safety challenges that working underground can pose.

A spokesperson for the BTS said: "Following the success of the Underground Health & Safety Course over past years it has been decided to repeat the two-day format of the last seven years to allow more time on specific subjects and include more discussion and debate."

Online booking is available on the BTS website: www.britishtunnelling.org.uk

Fees: GBP 170 for non-BTS members and GBP 130 for members

The preliminary schedule is as follows:

DAY 1 - UNDERGROUND RISKS

- Ground risks & how mitigated
- Health & Welfare for underground workers –noise, dust, heat, pollution, harmful gases
- Occupational Health programmes –Emergency Response
- Compressed Air Usage
- Underground Safety Passports, Competence, NVQs
- Debate - tba

DAY 2 - UNDERGROUND SAFETY

- Safety Management & Maintenance aspects of the use of Underground Machinery – including TBM, Loco, Rolling stock, Conveyors
- Electrical Safety - supply systems, management, safe usage
- CDM Regulations as applied to design & construction of Underground work.
- Use of Explosives underground
- Joint Code of Risk Management for underground works
- Safety Management & Leadership programmes
- Environmental Impacts/Sustainability issues
- Course review & candidates assessment

Contract awarded on Toronto's RER

CANADA — The 4Transit joint venture, comprising Hatch, Parsons, and WSP, announced on 24 August that it had been awarded a CAD 300M (USD 248M) contract for providing technical advisory services for two major work packages tendered under Metrolinx's 10-year Regional Express Rail (RER) Capital Program.

The RER Capital Program – a CAD 13.5bn (USD 11bn) undertaking that also includes a CAD 7bn State of Good Repair and Optimization and Expansion program – is designed to transform the GO Transit rail network in the Greater Toronto and Hamilton Area (GTHA) to a two-way, all-day electrified service, where trains run every 15 minutes or better.

This program will significantly boost the frequency and overall number of trips the GO Transit system offers in the region.

Metrolinx said it anticipates increased GO Transit ridership to at least 127 million customers within five years of the RER Capital Program's completion and expects to reduce journey times for select cross-region transit trips by as much as 50 per cent.

Mike Johnson, Parsons' infrastructure group president, notes, "This massive transformation of the GO rail network represents the convergence of innovative technology and a fast-track infrastructure expansion that will benefit everyone in the GTHA."

The companies created the 4Transit joint venture on April 16, 2009, as an unincorporated joint venture, with each of the three partners – WSP Canada Group Limited, Hatch Corporation and Parsons Inc. – contributing an equal one-third share. The partners share past experience delivering technical expertise on multiple large-scale transit projects such as Eglinton Crosstown LRT.

It is governed by an executive committee comprising one representative from each partner company.

EBC awarded Lavigne project

CANADA — EBC announced on 24 August that it had secured the CAD 39M (USD 32M) Lavigne Retention Pond Phase 1 contract from the City of Montreal.

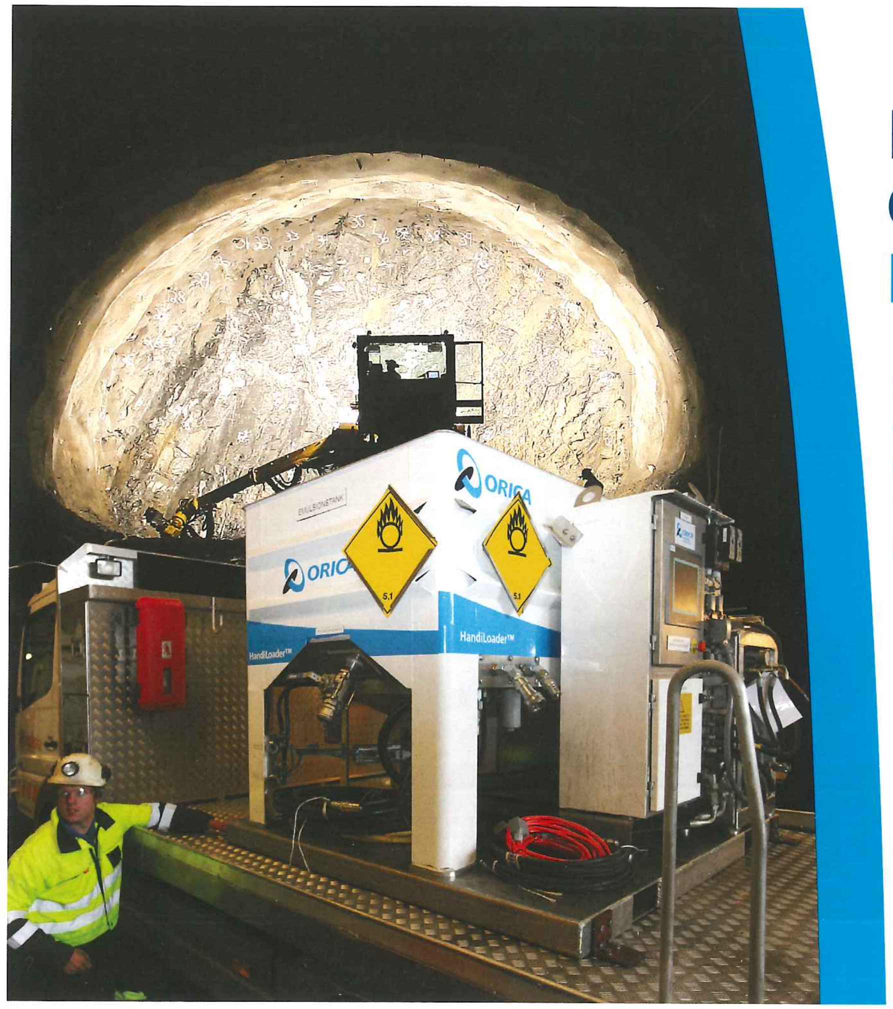
The purpose of the project is to reduce the numbers of spills in the des Prairies River and to increase the service level of the Gouin Collector.

Phase 1 comprises construction of tunnels and shafts located in the Ahuntsic-Cartierville and St-Laurent districts. EBC's work includes shaft construction of 42m in diameter and 25m depth; excavation of three tunnels for a total length of 2km, which will see installation of 1.8m diameter pipes; as well as the construction of three shafts located within the path of the three tunnels, one shaft per tunnel.

EBC said it has chosen to excavate the three tunnels which by drill and blast.

The 425-day project will start in October and will end in December 2018.

Left: The first of two slurry machines destined for the UGC03 contract of Mumbai Metro Line Three underwent factory acceptance in September. See news, page 7



WHY HOLD BACK THOSE TIERS

Martin Knights looks at the process of cooperation and innovation, and calls for a more collegial approach

AT THE RECENT ITA Training Course in Bergen, Norway, which preceded WTC, I gave a talk about the development of soft ground tunnelling from Victorian times until now. During preparations for the talk I looked at some tunnel project specifications for big projects and, up until 10 years ago, there had been a tendency for over-specification that had restricted contractors and equipment suppliers to past tried-and-tested practices. Where had been the opportunity to innovate and trial ideas by those best suited to introduce best and new practices?

The situation has improved in recent years as contemporary front end procurement has increasingly included ideas from the contractors, manufacturers, etc., during the preparation of contract documentation.

That reminded me of a challenge given to me in November 2009 at the Stuva Exhibition. ITA colleagues and leaders from the tunnelling world, took part in an industry round table talk. I was President of ITA then and the afternoon discussion concluded with industry leaders asking me, "So, Martin, what can we and the industry do for ITA? We provide sponsorship, like other leading tunnelling companies; we fill the exhibition halls; we host social gatherings during ITA conferences; we give lectures promoting new products. But we as equipment manufacturers and suppliers want to play a bigger technical role."

Stung by the perception that ITA was perceived to be undervaluing the talent that provided innovation in tunnelling, ITA set about forming Itatech, and prepared the ground to launch it as the premier promoter within ITA of technology and innovation. Our purpose was to prepare independent and commonly-agreed technical guidelines and evidence that had been jointly agreed by the whole ITA tunnelling industry, which is what Itatech continues to do. It provides manufacturing, installation, equipment and materials guidelines for contractors and designers and seeks to create confidence for tunnel owners that the 'brand' of the ITA is overseeing this important knowledge transfer.

WHERE CREDIT IS DUE

Soft ground urban tunnelling owes a debt to the development of TBMs over the past 40 years, and particularly the past 10. We can now do things that were too difficult to do in the past. It's no coincidence that the innovations in the last 50 years were led by TBM companies like Robbins, Lovat, Seli, Herrenknecht, etc. The leadership and pioneering spirit could have only been driven by the individual passion that comes from a 'family run' business. With time, growth and ownership has been passed on; the spirit of innovation in tunnelling needs to continue. Itatech has tried to capture that spirit and the steering board and activity groups include industry leaders who reflect the desire of industry to educate, improve and share.

A recent president of the UK Institution of Civil Engineers compared our fragmented industry processes with the manufacturing, aircraft and car industry. In effect he said "Why – unlike those industries – do we separate inception, planning, and design from assembly, installation and construction?" The infrastructure and mining industries rely on many different processes, procurement and partnerships to deliver projects precisely because they are so fragmented and siloed.

Contemporary procurement encourages more partnerships, but this doesn't make it less convoluted. We see the rise of the dreaded words "industry supply chain" and "second and third tier partners", where it strikes me that we're inadvertently airbrushing out the unique identity of those in the 'lower tiers' who innovate and provide the substance that nourishes the technical solutions that feature in new developments. Sadly, I have seen technical solutions get misinterpreted as ideas and solutions move up and down the so-called supply chain, begging for recognition, understanding and realisation of value.

I'm sure that this is not intended, but it happens. By validating and bringing innovations to the forefront through organisations such as ITA and BTS, we can improve some of the convoluted procurement and technical approval process. However, if we want to continue to see advancements like we've seen in urban soft ground tunnelling in recent years, we should seek to work closely with all 'tiers' involved.

Martin Knights
Martin is a former president of the International Tunnelling Association

EYES ON THE PRIZE

The BTS Harding Prize recognises outstanding performance in the tunnelling industry by young engineers under the age of 33. **Sally Spencer** spoke to this year's winner, Transport for London's Omar Mohammed

***Above:* Omar Mohammed, centre, was awarded the prize**

Sally Spencer
Sally joined the *Tunnels and Tunnelling* team as a contributing editor in 2015

THIS YEAR'S HARDING PRIZE winner says he has his parents to thank for fostering his interest in the built environment.

Omar Mohammed, a project engineer with London Underground, spent his early years in Cambridge and it was here that his mother, an architect, encouraged him to appreciate the many grand buildings in the university city.

"My parents didn't push me into civil engineering but they always encouraged me to look at where I could go and what I could achieve," Mohammed says.

In 2002 the family moved to Sheffield where Mohammed continued his schooling before going to the University of Leeds to study for a Masters degree in Civil and Structural Engineering.

"My strengths were in maths and physics so when I got to my A Levels my parents advised me to pick the subjects I enjoyed and that would also lead to a decent profession. Some people study their favourite subject but then find it's harder to field that degree in the real world – I was able to tick both boxes."

He realised he had a flair for engineering in his last year of A Levels when his school took part in the Engineering Education Scheme.

"They picked four of us and paired us with a local engineering company, Pandrol Track Systems, who make rail clips. They presented us with a problem they had on the manufacturing line regarding the insulator that goes over the top of the clip and asked us to come up with a solution. We wrote a report, did a presentation and won a Duke of Edinburgh Skills Award for it.

"That was my first taste of engineering in real life and of applying my maths and physics study into problem solving."

His exposure to tunnelling was fairly limited during his degree studies although he did study soil mechanics and geology under Terry Cousens.

"To be honest geology wasn't my favourite subject as I still preferred pure maths and cement chemistry and things like that," Mohammed says. "But actually, when you get into the industry geology is a completely different ball game and it's very interesting."

His dissertation was on the durability of concrete containing cement replacement materials with Leon Black.

"I wanted to explore the issue of climate change and how by improving the durability of concrete we could ensure better structures, longer life and reduce its CO_2 impact," he says.

He was drawn to the subject after working on a module that explored material properties, including the possibilities of making concrete more durable and environmentally friendly.

"It was a really good module," he says. "They had a really good way of relating it to real life, such as how by changing the mix a little you can prevent concrete cracking and why that is so important in the long term.

"My professors were very supportive and that built an interest in cement constituents and concrete mixtures. Concrete isn't just sand, cement and mortar, it's complex chemistry at work."

His interest in concrete has continued into his career and has stood him in good stead with SCL tunnelling projects.

"One of the biggest challenges of SCL tunnelling is the logistics. If one part of what is essentially your production line fails it causes ground movement, programme and cost issues. It's important to get the mix right, not just so it is consistent and delivers the quality you need but also to prop up that production line and minimise your impact on third parties."

ENTRY TO INDUSTRY

On leaving university in 2012, Mohammed went straight into Transport for London's graduate scheme where his first placement was with what was then called the Strategy and Service Development Directorate.

"One of the first jobs I got was helping out with a guidance document for new lines and extensions," Mohammed says. "It had been in production for quite a long time but I was asked to close out the final reviews and comments and put the finishing touches to it. It gave me a really good overview of how the London Underground (LU) business works."

Towards the end of that placement he also gained some experience of offsite manufacture, relating to station and platform construction, before moving on to the civils maintenance team. Here he worked as an assistant area manager to the Sub Surface section of the LU network.

"My first job was on a severely damaged parapet on a retaining wall that was overhanging the track. I had to go out and get the design and then seek the permission of the building owners behind the retaining wall. I negotiated with about six stakeholders, so I was really able to hone my people skills."

His next move was to the Victoria Station Upgrade – and this is where he first got bitten by the tunnel bug.

"I wasn't immediately in a position of great responsibility, of course, but I was given a lot to help out with and towards the end of my placement I was involved with third party stakeholders again," he says.

Above: 3D representation of Bank site footprint

"Across the road from Victoria station there was the big Nova development project going on [a mixed use development of offices, apartments and restaurants] and took the lead in the infrastructure protection role. I was the interface between Nova and LU on engineering and ground movement issues."

By this time Mohammed was keen to acquire some design experience, so he and a fellow graduate trainee pitched for a secondment to Dr Sauer & Partners on the Bank Station Capacity Upgrade.

"We needed the experience for our Institution of Civil Engineers attributes and were looking for pure tunnel design experience – so doing the design ourselves rather than reviewing designs submitted to us.

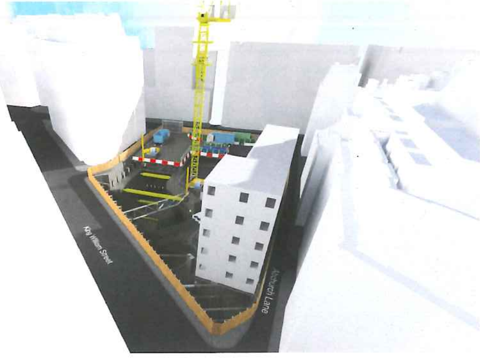
"It was a benefit for TfL for us to join Dr Sauer & Partners and acquire some pure SCL design experience and it was a benefit for the project as at that stage we were a free resource.

"There is a good relationship between LU and Dr Sauer – and the other tier two contractors at Bank," continues Mohammed. "And I think we set a precedent because graduate trainees since us have gone on to secondments at Dr Sauer."

The secondment lasted a year and when Mohammed left, he also came out of the TfL graduate training scheme and went into the "career launch position", whereby he was placed elsewhere in the business.

"Having been at Bank for some time I wanted to stay here," he says. "My first major role was as project engineer and tunnels package manager for the Bank Bloomberg Place upgrade project."

Bloomberg's new European headquarters are due to open in the heart of the City of London this autumn and LU has leased a structural basement box and has a contract with Hochtief to fit it out with escalators and lifts and to construct two adits connecting the box to the Waterloo and City Line platforms (this



Above: *A paper on Mohammed's work at Bank won him the Harding Prize*

line is part of the LU network and operates as a shuttle service between Waterloo and Bank stations, with no intermediate stops).

"As I had some tunnel engineering experience I was quickly moved into the position of being responsible for the adits from project management and project engineering points of view.

"It was a challenging project because we were working right by the station and obviously had to think about ground movement. Co-ordinating works was also testing – for example, we had a passageway closure and had to ensure we utilised that much as possible and delivered as far as we could within that closure."

Another major challenge was that when Mohammed came to the project there was a methodology change from SCL to traditional squareworks.

"It was an opportunity for me to learn a different aspect of tunnelling and traditional timber tunnelling is definitely very interesting, but it also meant we were under pressure to get the design and construction under way because the change meant we'd lost a little bit of time."

He adds that while, of course, he wasn't left to deal with these issues alone, exposure to this sort of challenge was an extremely useful part of the learning curve.

"It stood me in really good stead to get my chartership as well," he says. "Chartership often asks for that next level of responsibility and that is something that is harder to get as a graduate because if you are only on a project for six or nine months it's difficult to reach a position of authority."

The adit structure and waterproofing was completed in January this year and Mohammed was then invited back to Dr Sauer to join the Site Supervision team as an SCL engineer.

"It was certainly rewarding to see the design I helped put together being built, and I think my experience of the design was useful when it came to its implementation."

Mohammed is now working on the station box at Bank. "We've just started the piling, so I am looking after that and then we'll be in excavation work at the end of this year/ beginning of next."

Having joined the Bank Station Upgrade project shortly after concept design, Mohammed is keen to see the project through and he is looking forward to the time when he can put his name on a project and leave a lasting and tangible legacy.

"To be able to say I've delivered this station box would be a great step up so for the next couple of years I'm focused on making sure this gets built on time and to a good quality."

At some point in the future, however, he would like to gain more "early stage" experience, such as route planning.

"I'd like to experience shaping a project from a contract point of view, going out to obtain land and planning permissions or TWAO (Transport and Works Act Orders) applications and so on. I had a taste of that early on in this [Bank] project and it would be good to go back to something like that. I don't want to stay in construction for the whole time – I would like to jump around the life cycle because I think that makes you a better engineer."

One gap in his tunnelling experience he would like to plug is working with TBMs.

"There would have been an opportunity with Crossrail but at the time I was looking at tunnelling I was already working at Victoria, which was an SCL job and I also wanted to get my design experience, so it didn't make sense to switch to a different type of tunnelling at that point."

HARDING PRIZE

In the meantime, of course, Mohammed won this year's BTS Harding Prize for his paper and presentation on deep pile foundation interceptions in tunnelling at Bank Station.

"I chose the subject because I think it should be talked about more," he said. "It's something we are increasingly going to be facing and there aren't many papers out there on pile interceptions.

"I had finished my chartership the year before and I like to give myself a goal to work towards. If you take life in bite-sized chunks and work towards goals that enable you to take the next step, it will help you progress. It's all about self-improvement.

"Winning the Harding Prize is beneficial to me not just because of the personal attribute but because of the experience – it will help me grow as a person. And I must thank LU, Dragados, the principal contractor on Bank, Dr Sauer and all the other tier two contractors for the huge support they gave me."

It is this kind of support Mohammed is keen to provide himself in his role as a STEM (science, technology, engineering and mathematics) learning ambassador. He has helped out with activities at schools and at open days at the London Transport Museum and has helped judge engineering models in the Big Bang competition.

"It's really important to promote the STEM subjects very early," he said. "When I was at school the questions that got asked most often were 'why are we doing this?', 'what does it matter?', 'when am I going to use this in real life?', so it's important to explain how learning can be applied and, also, how to follow a route to a career." He added that he believes the fundamental issue underlying the skills gap is that most young people don't really understand what civil engineering is.

"Building a project like the Bank Station Upgrade requires people from all different backgrounds and disciplines, from surveying and planning through to number crunching and construction," Mohammed says.

"Encouraging younger generations to feed this skilled work area is vital."

DEEP PILE FOUNDATION INTERCEPTIONS IN TUNNELLING AT BANK STATION

This article is a reproduction of **Omar Mohammed's** Harding Prize winning paper. The original can be found on the BTS website

Omar Mohammed
Omar worked as a project engineer on the Bank Station Capacity Upgrade

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LU Track Design Team

BANK STATION CAPACITY UPGRADE (BSCU) is a congestion relief and interchange improvement project for London Underground (LU) in the City of London. The project is currently entering the construction phase, working to relieve the issues highlighted in Figure 1.

The infrastructure improvement proposed as part of the Transport and Works Act Order (TWAO) submission includes:

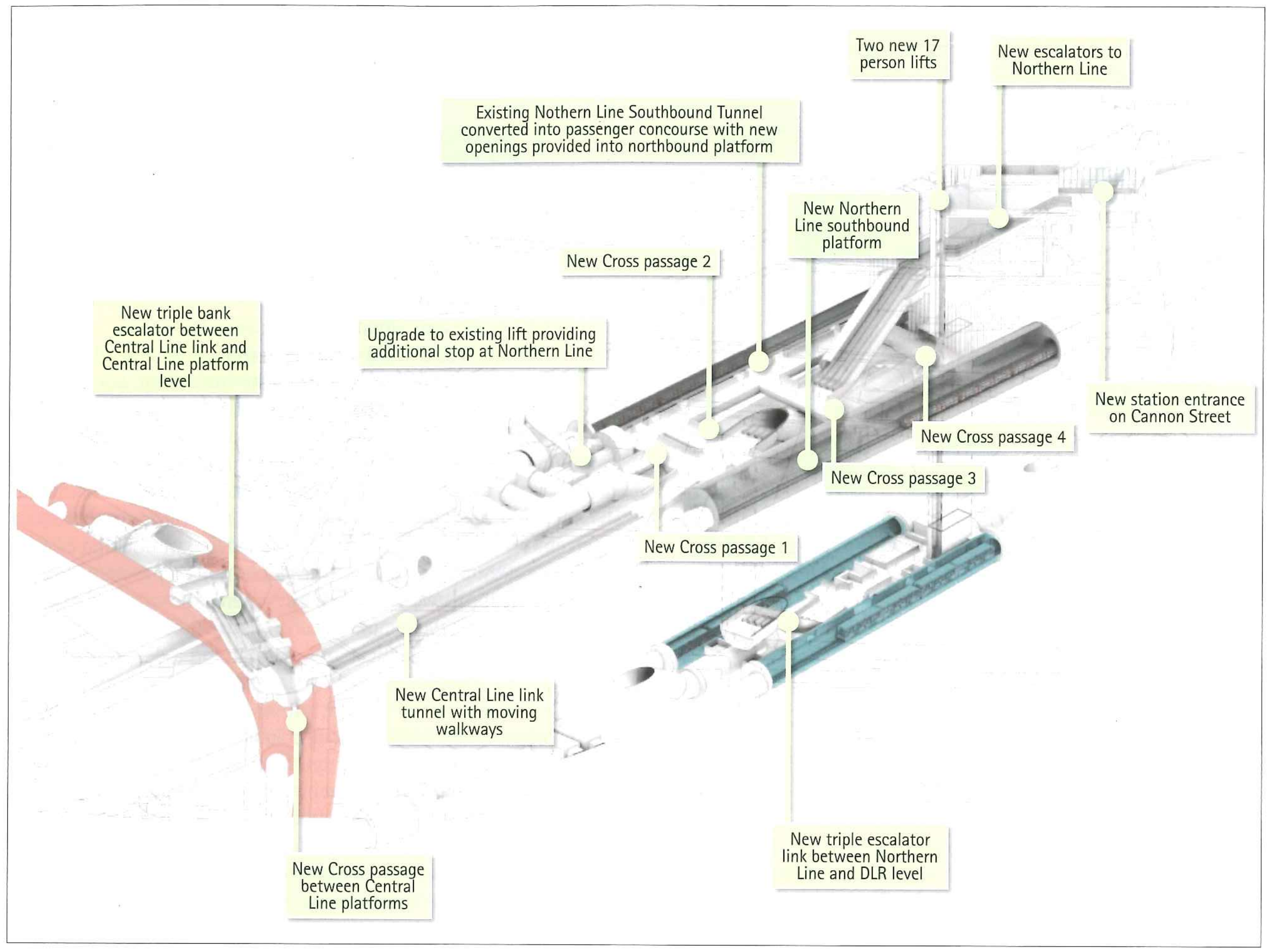
- Improved below ground interchange capacity including a new southbound running tunnel and platform for the Northern line,
- New station entrance on Cannon Street,
- Step-Free access from platform to street for the Northern line and DLR,
- Moving walkway for improved journey times to the Central line,
- Additional lifts and escalators to ease congestion and improve accessibility,
- Improved fire and evacuation routes.

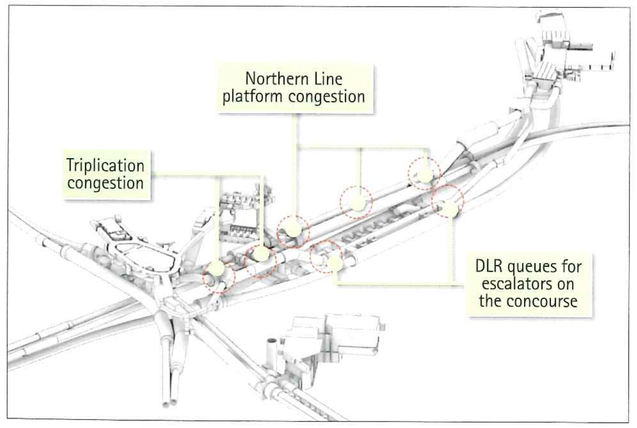
Bank Bloomberg Place (BBP) is the sister project to BSCU and is also currently in construction. As part of the planning permission for the new 3.2 Acre Bloomberg European headquarters (Figure 3), provision was made for a station box to the Waterloo and City line within the developer's basement. The structure was constructed on behalf of Bloomberg by Robert McAlpine, to be leased by TfL.

The box fit-out and the connection to LU tunnels was then procured through a design and build contract with Hochtief UK. The new entrance provides step free access to the Waterloo and City line as well as reducing congestion and improving emergency evacuation times for the wider station.

One of the many challenges for both projects is the potential impact on a number of third party stakeholders throughout design and construction. This is particularly apt for an area in which approximately 80 per cent of buildings are within a conservation area, with historic national landmarks and international financial centres in close proximity.

In defining the alignments for the new tunnels a key consideration was whom and what the projects would impact, and how LU would either avoid, mitigate or manage these interfaces. Building foundations in particular would require attention.





Alignment

The need for additional underground space at Bank was clear, however delivering this space while minimising/avoiding impacts with respect to ground movement, underground obstructions and noise and vibration in this densely-populated area would require detailed planning of the alignment.

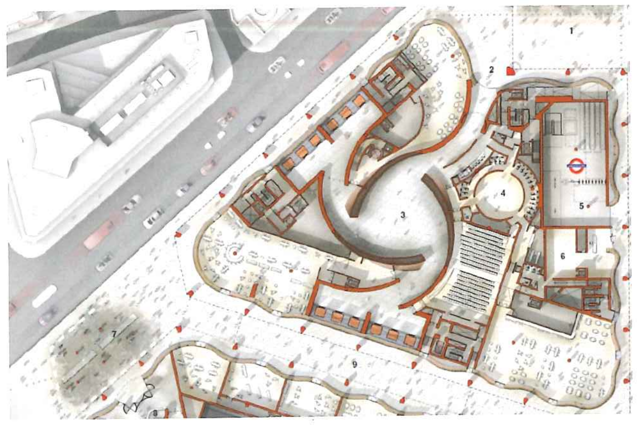
An alignment envelope was identified and an initial desktop study conducted to provide information on building locations and their foundations.

Ultimately the project agreed that trying to accommodate or avoid underground obstructions would be counter intuitive. Avoiding foundations would result in a longer tunnel and therefore additional excavation and ground movement.

Top: Figure 2, Proposals to improve; capacity, interchange and provision of step free access

Above left: Figure 1, Examples of common issues at the Bank/Monument complex, leading to requirement for an interchange and capacity upgrade

Above right: Figure 3, New Bloomberg EU HQ on Queen Victoria St. The basement of this building would provide space-proofing for a new Waterloo and City line station entrance



Above: ***Figure 4, Plan section of Bloomberg Complex. The LU box is indicated by the roundel***

As a result the alignment that was straightest and smoothest (and hence held the greatest benefit with respect to line speeds) was chosen. The ground movement, noise and vibration and underground obstruction risks would be addressed by the tunnel design.

The Bank Bloomberg project did not identify any potential underground obstructions during the alignment definition and therefore could proceed with low residual risk of potential, unknown foundations – particularly considering its proximity to the existing LU tunnels (which had no record of underground obstructions being encountered).

FEASIBILITY

Desktop study

Once the alignment was defined, the potential impacts on each building along the route could be estimated. A desktop study was conducted to look into the foundation structures for each building above the alignment of the tunnels. Detailed research of public archive records, as well as discussion with building owners yielded greater detail in the foundations that may be intercepted across the route.

Where as-built pile depths could not be found, back calculation and engineering judgement was used to define conservative estimates on potential depths, types and the materials used. The foundations could then be modelled within the project workspace to better quantify the risk of interception and potential impact.

A single set of 'pile general arrangement' drawings was then created. This would collate all sources of research and information into a single location, and would enable the future construction team to quickly identify any potential interceptions.

Any assumptions made at this point would be recorded within the project assumptions register, for resolution or confirmation and consideration within other aspects of the project design.

Scope definition

A physical clash between the tunnels and foundations would instantly create an interface with the building. These could be dealt with at the tunnel face or potentially through works at surface level (such as underpinning).

However additional interfaces could still arise through noise and vibration impacts in the permanent state caused by train movements in the tunnel. The submitted TWAO had committed to minimise noise and vibration. To achieve this with a standard track-form required a 1.5m clear separation from any pile.

Achieving 1.5m separation within the tunnelling works would be extremely challenging, particularly with the residual risk of unknown piled foundations along the route. As such, noise and vibration would be best addressed through the use of a high performance track form, reducing impact at source.

Any additional ground movement impacts through interception would also need to be considered in building damage assessments; however this could not be progressed until potential solutions were drafted. The interception design would therefore progress while aiming to minimise excavation volumes as far as reasonably practical and maintaining a dialogue with the engineers responsible for these assessments.

From the work done to date and review of the model, the pile interceptions could be divided into four scenarios:

- A redundant pile is encountered; previously separated from the building above (e.g., temporary works),
- A redundant pile is encountered; not separated from the building above (e.g., historic piles not broken out),
- Live pile encountered; where interception would reduce ultimate capacity but maintain design load through a reduced factor of safety,
- Live pile encountered; where interception would reduce ultimate capacity substantially, meaning load would need to be shared to neighbouring structures or through a newly created transfer structure.

The risk profile for this work could now be quantified based on three factors, including the impacts above.

Likelihood of interception was assessed against a 500mm and 150mm offset from the tunnel springline. This would account for potential plan tolerance or out of verticality. The confidence in the data would be assessed against its source, or whether it agreed with previous modelling data at tender stage.

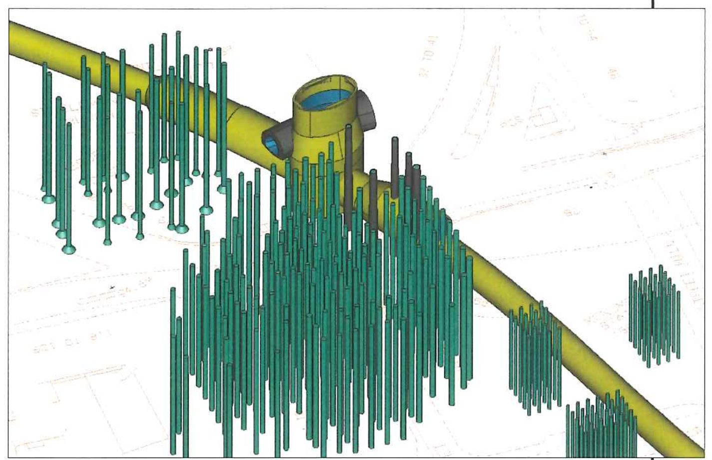
Above: ***Figure 5, Initial Alignment 'window' in blue***

Pile assessment

Likelihood of interception	*Confidence in data*	*Impact of interception*
Are the piles (as currently modelled) • Outside the 500mm zone • Inside the 500mm zone • Inside the 150mm zone • Within Tunnel alignment *NB: Assuming depth of piles clashes with the BSCU Tunnels*	How confident are we of the pile location in plan or depth? • Surveyed location • Good agreement with 3D model • Poor agreement with 3D model • No/limited/unreliable information	Which proposed solution would be required? • Redundant pile, separated from building • Redundant pile, not separated from existing structure • Live pile, where reduced F.O.S could be used • Live pile where Transfer structure would be required

The author presented this data to engineering management for Dragados and LU. For each intercepted building the author proposed an overall level of risk then suggested where additional surveys could be conducted, or more information could be requested from building owners to mitigate these risks. Where a designed solution looked the most likely scenario further information would be gathered on the capacities and design loads of live piles.

Concurrently, the planning and consents team were negotiating with building owners to facilitate the TWAO application in preparation for a public inquiry legal agreements were reviewed by all parties within the project to ensure commitments made did not preclude any initial solutions considered. LU's view was to achieve separation wherever reasonably practical. This would not only simplify the design; but limit any potential ongoing relationship with third parties with respect to noise, vibration and future support, construction, demolition and maintenance – something third parties would likely be keen to avoid.



Above: ***Figure 6, An example of the 3D modelled foundations for three buildings in the Arthur Street area***

CONCEPT DESIGN

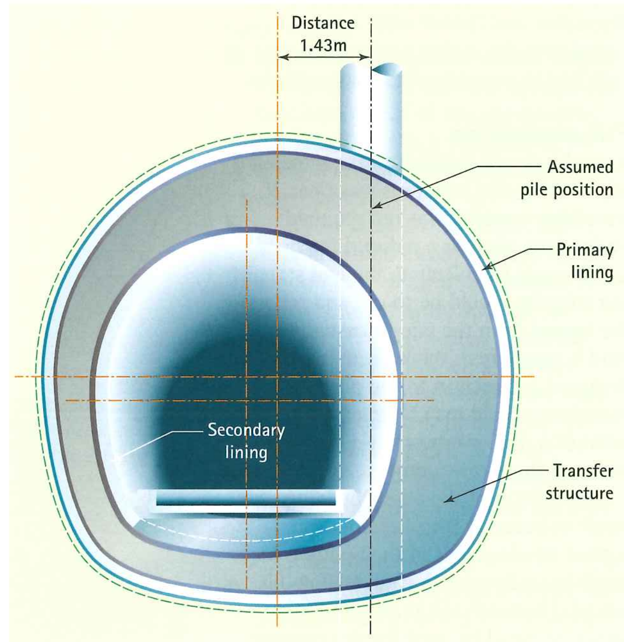
Load transfer interceptions

With factors of safety for building foundations usually between 2.5 and 3.5, and often found to be higher with the more detailed analysis and information on soil conditions that can be conducted and found today, the transfer option can often be discounted. This assumes however, that the building owner is willing to accept a limit on future, more aggressive re-utilisation of their piles. In cases where future construction is planned or desired, or where factors of safety would be reduced to unacceptable factors of safety, transfer options should be explored.

Initially, back analysis was carried out to validate the ability of the foundation system to redistribute load. If a pile is cut or undermined, the load within the pile may temporarily move towards surrounding piles; and the pile cap and slab must have sufficient capacity to allow for these changes. While the piles themselves may have a great deal of spare capacity, this redistribution could lead to settlement and potential cracking of the structural slab. This may in turn lead to intolerable serviceability concerns and hence a solution must be found without any temporary loss of support.

Similarly, if neighbouring piles do not have sufficient capacity to carry the load lost by the interception; the settlement effects may be too large for the building once again limiting any temporary loss of support.

A 'cut then support' option (Figure 7) would assume any load redistribution or settlement affects from the interception were acceptable; allowing the pile capacity to be temporarily reduced and eventually replaced by a transfer structure within the tunnel



Above: ***Figure 7, Initial concept of a transfer solution. The grey indicates the standard SCL secondary lining, blue indicates the existing pile structure, red indicates a compressible fill used to separate the third party structure from the SCL, light green indicates the transfer structure and dark green indicates initial primary lining sprayed for temporary support during transfer structure works*** excavation, restoring capacity. A compressible fill material could be used to ensure any future load change in the pile (and settlement or heave) would not impact on the LU tunnels.

The initial tunnel excavation could proceed similarly to a pilot tunnel, through localised breakout of the foundation. An enlargement can then be created to mechanically fix to the pile and provide an end bearing section of equal capacity to the intercepted pile length while incorporating the 'physical separation layer' to allow for future movement. This would also allow the initial tunnelling works to proceed quickly and hence minimise ground movement.

For a 'support then cut' solution (Figure 8), large initial excavations would be required to enable installation of temporary pile supports. Unlike the 'cut then support' option the remaining works could not proceed until the temporary support structure is created. Additionally, the large excavated volume could potentially introduce buckling effects onto the pile, leading to cracking and hence serviceability issues.

Both options while structurally feasible would require detailed analysis with respect to ground movement, constructability, the building's structure/ damage impact and presentation to building owners.

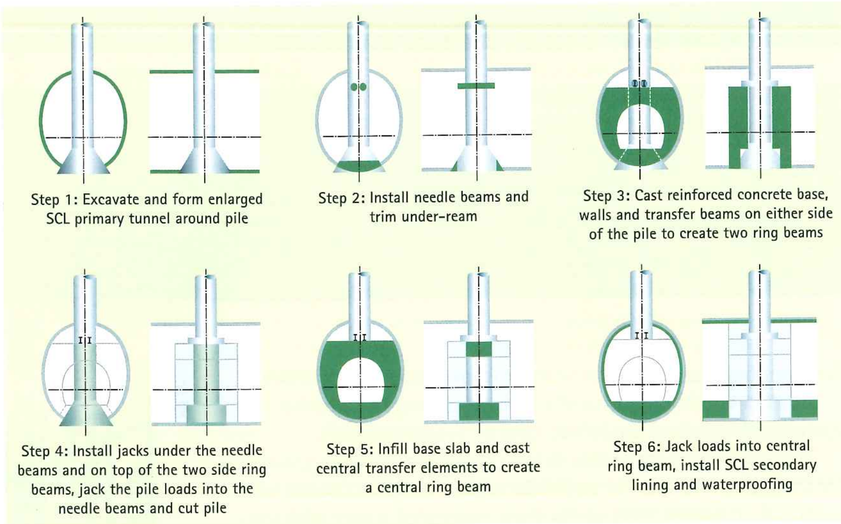
While these options were tabled for discussion and further work was completed, the author's primary focus switched to non-transfer design options.

Pile separation

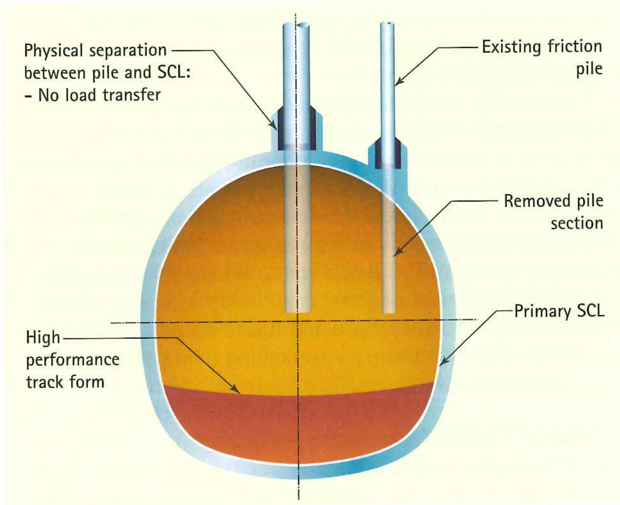
A single, simple solution to the remaining pile interception scenarios was clear. If remaining capacity was not required (redundant piles) or a reduced factor of safety could be tolerated, the end state of our solution would be to cut and separate the tunnel from the pile to ensure no load is transferred. While there may be no designed connection to the piled foundation, load may be transferred without a gap or movement joint between the two structures.

Demolition of the above building may result in heave at the pile's toe, and further development of the building may result in settlement. A compressible fill material between the tunnel and pile structure could be used for this purpose, enabling physical separation (Figure 9).

The next steps would be to progress the detailed excavation and support sequence, review the constructability and determine the extent of potential movement (and hence separation requirement) for the final design of live separation piles.



Above: Figure 8, Concept design option submitted as part of TWAO evidence, showing temporary works to maintain full pile load throughout



Above: Figure 9, Concept design sketch submitted as part of TWAO evidence, showing separation for piles not requiring load transfer

DETAILED DESIGN (PILE SEPARATION)

Pile Movement

To determine the physical separation and then the additional local breakout required about each pile the degree of future settlement and heave that may occur must be calculated.

The capacity of a typical pile was calculated initially, both before and after interception.

This would validate any reduction in the factor of safety and confirm if they are acceptable.

The pile's potential settlement and heave could then be calculated by assuming the pile is first fully unloaded (demolition) and subsequently loaded to its new (now reduced) ultimate capacity mimicking the worst case load, and hence movement, scenario.

Any potential heave could be estimated using empirical ground movement calculations; however it is highly unlikely that the building would heave due to relaxation to the same magnitude that it may settle from loading. Therefore any settlement that can be accommodated by the separation material could similarly accommodate heave.

Below: Equation 1, Extracts from the London District Surveyors Association Guidance Note for design of bored straight shafted piles in London Clay (2000), used to back calculate the pile capacities. The ultimate base capacity (Qb) would be removed upon interception, along with a reduced shaft capacity (Qs) due to reduced length

$$\text{(i)}\ Q = Q_s + Q_b$$

where Q_s = ultimate shaft capacity
where Q_b = ultimate base capacity

$$\text{(ii)}\ Qs = \pi\, DL.\, \alpha\, .\, c_u$$

where D = pile diameter (m)
where L = pile prenetration in London Clay (m)
α = average adhesion factor over shaft length

c_u = average undrained shear strength over length L determined from unconsolidated undrained (UU) triaxial tests on 100mm diameter undisturbed samples (kN/m^2)

$\alpha\, .\, c_u$ should not exceed *140 kN/m^2 except where a higher limiting value is proven by a pile load test

**This approximates to a maximum Cu value of 235kN/m² based on an upper a value of 0.6*

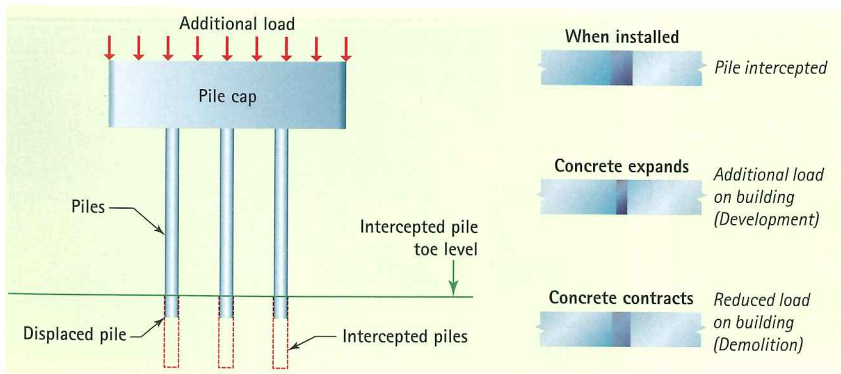
$$\text{(iii)}\ \frac{Q_b}{4} = \pi\, D^2\, .N_c\, .\, C_{ub}$$

where D = pile diameter
where: N_c = bearing capacity factor = 9 for circular bearing piles
where: C_{ub} = undrained shear strength at the pile base measured in UU triaxial tests on 100mm diameter undisturbed samples

Below: Equation 2, Extract from Poulos, H. G. et. Davis, E. H.: Pile Foundations Analysis and Design. (1980) where the maximum settlement (Slim) due to loading is calculated based on the point at which shaft resistance no longer increases and any further load is taken by the pile base

$$s_{lim} = \frac{I.R_{bu}}{\beta.d.E_s}$$

where: I = settlement infuence factor [-]
R_{bu} = ultimate pile base bearing capacity [N]
β = proportion of applied load transferred to pile base [-]
d = pile diameter [m]
E_s = average value of secant modulus of soil along the pile shaft [MPa]



Below: Figure 10, When additional load is introduced into the piles, settlement will occur at the toe until skin friction is mobilised. The compressible fill would contract to accommodate this movement

Building damage

Settlement of the building and its foundations during the excavation can initially be calculated empirically, with further detailed analysis conducted if deemed required (following LU guidance for staged assessment). Previous experience from the Jubilee Line Extension and Channel Tunnel Rail Link has found that piles largely settle with the ground and horizontal movements can conservatively be estimated to match Greenfield soil movements. Much of this movement would occur ahead of the tunnel face.

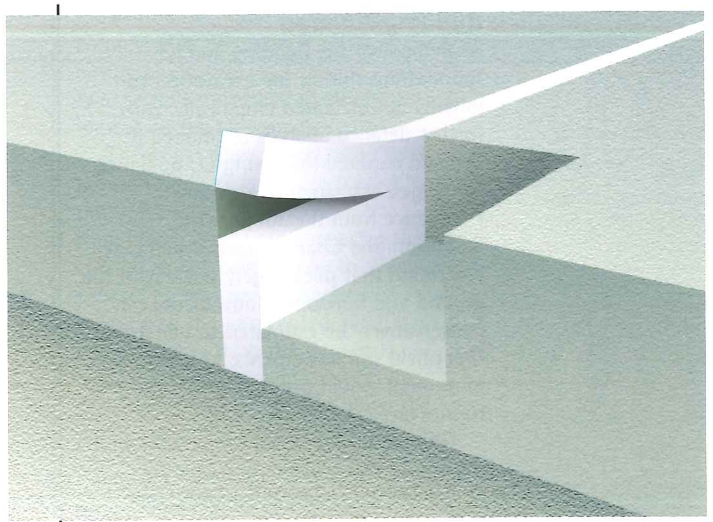
One important factor to consider with this movement was the potential for buckling, particularly if the piles were (when considered as a concrete, unreinforced column) classed as slender. In these instances a check on buckling capacity was completed to ensure any lateral movement of the pile would not lead to cracking and therefore serviceability issues. Any instances where buckling would lead to damage would have to mitigate ground movement further, potentially through reduction of the excavation section size.

Material requirements

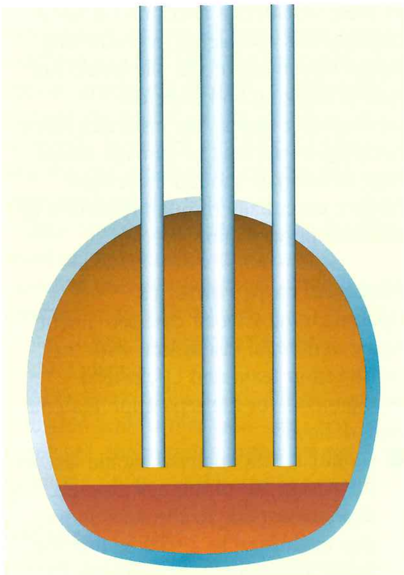
Upon defining a worst case settlement figure and initial discussions with the construction team and LU; several requirements for the separation material were defined:

- Durability; the material should last for the design life of the new tunnels. Any degradation due to the surrounding clay could lead to a void behind the lining and a potential weakness to water ingress.
- Ability to spray against (SCL); the material would ideally need to robust enough to withstand the sprayed concrete lining being applied; to ensure as far as practically possible that the excavation sequence can continue as normal without the need for additional plant or material
- Compressibility/elasticity; to act elastically within the loads required while maintaining a minimal thickness to prevent the need for over-excavation
- Ease of installation; with many of the interceptions occurring at the tunnel crown, the weight and handling of the material would be important to ensure effective and safe installation

Several options were found and an initial material was chosen based on research into joint fillers used in reinforced concrete construction. Based on the settlement requirements and the



Above: *Figure 11, Flexcell joint filler often used to fill construction joints in RC slabs*



Left: *Figure 12, An example of one particularly congested area during the tunnelling works*

material properties a 150mm thick Flexcell compressible fill material was selected for confirmation by the contractor pre-construction.

Excavation and support (SCL) development

Any design must ensure safety and efficiency in its development. Using the 3D model and input from the construction team, some of the key CDM risks could be further identified and eliminated or mitigated. As mentioned above, working from height and the working area would be a key risk to the installation of any separation. Furthermore, any installation would require supported ground above any working operatives. The detail itself was developed with these risks in mind. Finally, several areas were heavily congested with foundations (see Figure 12). Ensuring the construction team could work around and cut/breakout these piles to progress the excavation, while ensuring plant, material and personnel are able to safely move underneath would be an important consideration for the design.

Taking these requirements into account the author created a detail that would locally enlarge to allow for future separation, while supporting the ground in the immediate vicinity of the pile to ensure the safety of personnel underneath the crown. All breakout would be completed mechanically, eliminating any risk of operatives working under unsupported ground.

Step one creates the local enlargement as part of the primary lining. This envelops the pile with an initial lining sufficient for temporary ground support. This allows the pile to be broken back partially to continue the excavation safely. The supporting layer would fail in shear if any long term movement is experienced, maintaining physical separation. Step two involves breaking the back and fixing the separation layer to the pile directly or to the surrounding temporary support. The separation layer is slightly oversized to allow for any potential lateral movement of the pile. Step three then installs post drilled fixings to allow for continuity in the lining and additional support for the fresh sprayed concrete. The remaining primary lining is then sprayed to standard profile.

The excavation and support sequence offered flexibility in both breakout and safe stop. By allowing the excavation to proceed past the piles, the excavation can progress to an extent; however a clear limit is placed on the advance length beyond any temporarily supported ground/piles. This ensures full ground support is sprayed before the excavation proceeds mitigating risk of further ground movement resulting in potential failure of the temporary support.

The design could now be endorsed by the construction team. Further lessons learned would capture best practise and issues faced from the industry to ensure the design was as robust as possible. The work that the Bank team had done to date was also shared with other areas of LU, including Crossrail 2.

CONSTRUCTION

Through colleagues in the tunnelling team some feedback was obtained from Crossrail C300/C410 (BFK) on pile removal.

Their approach largely agreed with design; however there was a slightly different approach to their application of final primary lining around the physical separation.

By introducing steel mesh around the physical separation membrane, the sprayed concrete would be better supported in its temporary state; remaining self supporting while the concrete gains strength.

Right: *Figure 13, Redundant pile encountered by Crossrail C300/ C410 (BFK)*

Left: *Figure 14, Physical Separation applied at C300/ C410 (BFK), incorporating a steel mesh*

Left: *Figure 15, The pile was initially left in place, to ensure checks could be conducted on its provenance; the face was timbered at this point to ensure personnel were not exposed to potential wedge/ block failures*

BSCU has not yet encountered piles but BBP did unexpectedly intercept two unknown piles. Using the knowledge obtained at BSCU, the author was able to assist in the design and construction of the interception. The tunnelling methodology here was squareworks but the general principles of the design were similar.

Ultimately both instances of construction experience have been a useful exercise in validating the design with first hand experience and they were successful in their implementation. It will be useful to see how future interceptions feedback on our design.

CONCLUSION

Tunnelling in London has been a regular occurrence for over a century. Previous tunnelling projects have perhaps avoided these obstructions; but this is becoming increasingly difficult.

The current and future demand for capacity coupled with the more densely congested nature of the underground (as well as above ground) space means that obstructions and impacts such as these will occur more and more often.

Additionally, LU's business plan hinges on moving customers quickly and efficiently through its stations and tunnels. With Crossrail 2 in the planning stages, and several station capacity upgrades entering feasibility or concept through the Future Stations Programme, the demand is evident in the near future. TfL's responsibility to its customers is to deliver an efficient and effective design with a sound business case for these projects.

Accomplishing these goals while ensuring third parties and stakeholders are not adversely impacted by the work will require new solutions. It is the responsibility of projects such as this one to pioneer the best engineering-driven and cost-effective design and construction. Innovative approaches such as interception design overcome these modern day challenges and our industry must continue to promote these with the view to providing reference material and knowledge for future projects.

The pile interceptions work at BSCU and BBP is something in which the author is truly proud to be involved. It is not only the engineering achievements tabled here that will stand future tunnelling in good stead, but the approach taken to overcoming these challenges. Collaborative meetings of engineers and construction managers from consultants, contractors and the client, yielded solutions that were innovative and forward thinking.

Building more than 1,200m of tunnel in the City of London is no easy task but the team at Bank have consistently risen to the challenge the construction phase will surely follow suit.

Above: ***Figure 16, A separation membrane was installed using a local breakout above the permanent works level. The work could be conducted under timber ensuring miners were not exposed to unsupported ground directly overhead***

DESIGN CONSIDERATIONS

ACI recently drafted a new report as the first design guideline on FRC tunnel segments to provide specific guidance for this emerging technology. **Mehdi Bakhshi, Verya Nasri** and **Federica Mercuriello** of Aecom discuss how to implement the ACI 544 Guideline into tunnel design

PRECAST CONCRETE SEGMENTS ARE installed to support the tunnel excavation behind the TBM in soft ground and weak rock applications. The TBM advances by thrusting off the completed rings of precast concrete segments that provide both the initial and final ground support as part of a one-pass lining system. These segments are typically designed to resist the permanent loads from the ground and groundwater as well as the temporary loads from production, transportation and construction. Tunnel segments are generally reinforced to resist tensile stresses. With traditional rebar, a significant amount of labour is needed to assemble the cages and place the rebar, which results in higher production costs.

Fibre Reinforced Concrete (FRC) can be used to enhance the production, handling, and placement of segments. This is because of the uniform dispersion of fibres throughout the segment to include the concrete cover, which is very advantageous for resisting the bursting and spalling stresses. These stresses develop as a result of the high loads induced on the segments during the TBM jacking process. The presence of fibre in the concrete matrix helps mitigate against unintentional impact loads during segment handling and tunnel construction.

The improved behaviour of the concrete due to addition of fibres generally results in smaller crack widths (Bakhshi and Nasri, 2015) and fewer problems with durability over the life of the structure. An increase in the crack width contributes to the ingress of the environmental agents into the concrete that can lead to the excessive water infiltration and occurrence of corrosion of steel reinforcement (ACI 544.5R, 2010). Two main deterioration mechanisms for corrosion include carbonation and ingress of chloride ions. Durability test results indicate that carbonation corrosion is limited to the surface regions of the steel fibre reinforced concrete (SFRC) and will neither lead to structural damage (cracking and or spalling), nor protrude to deeper regions of the SFRC (ACI 544.5R, 2010). The corrosion arising from cracks and chloride diffusivity may cause a decrease of the load carrying capacity of the SFRC element; however, this is usually offset by rust formation that increases the fibre-paste friction, thus enhancing the fibre pullout response, which can increase the flexural capacity of SFRC elements (Granju and Balouch, 2005). Regarding performance of FRC under fire, similar to reinforcing bars in conventionally Reinforced Concrete (RC), steel fibres have been found to have little or no influence on the prevention of explosive spalling and monofilament polypropylene micro-fibres are commonly used as the explosive spalling prevention.

Mehdi Bakhshi
Mehdi is a senior tunnel engineer with Aecom

Verya Nasri
Verya is the global tunnel lead, vice president for Aecom

Federica Mercuriello
Federica is a senior tunnel engineer with Aecom

Since 1982, FRC has been used in numerous tunnel projects around the world with internal diameters ranging from 2.2m to 11.4m, as the preferred material for the construction of tunnel segmental lining (ACI 544.7R, 2016). Minimum and maximum thickness of the FRC precast segments have been 0.15m and 0.40m, respectively. In most of the projects, small to mid-size tunnels with internal diameters between 2.2m and 7m have been reinforced with only steel fibres at a dosage ranging from 25 to 60 kg/m³. The design has been performed using constitutive laws recommended by international codes and standards such as

DBV (2001), RILEM TC 162-TDF (2003), CNR DT 204/2006 (2007), EHE (2008) and fib Model Code (2010). FRC technology has developed in recent years with the introduction of high performance concrete allowing the use of fibres as the sole reinforcement system for more challenging conditions on larger diameter tunnel projects. Tunnel rings of more than 7m internal diameter have been successfully constructed with FRC segments at Grosvenor Coal Mine, Channel Tunnel Rail Link and the Blue Plains Tunnel with internal diameters of 7m, 7.15m and 7m, respectively. When the slenderness of a segment, defined as the ratio between the developed segment lengths and its thickness, is higher than 10, it is generally necessary to adopt a hybrid reinforcement of fibres and conventional steel bars. However, some researchers have proposed to increase the slenderness limit up to 12-13. Full-scale tests are needed to validate the usage of fibres with such slenderness conditions.

Regardless of the advantages of FRC segments, their use has been limited due to lack of recommendations and guidelines. Within ACI Committee 544, a working group drafted a new report (ACI 544.7R. 2016) that is the first design guideline on FRC segments. This ACI document provides a design procedure for FRC tunnel segments to withstand all the appropriate temporary and permanent load cases occurring during the construction and design life of tunnels,

Table 1. Required strength (U) expressed in terms of factored loads for governing load cases

Load Case	Required Strength (U)
1: stripping	U = 1.4w
2: storage	U = 1.4(w + F)
3: transportation	U = 1.4(w + F)xd
4: handling	U = 1.4wxd
5: thrust jack forces	U = 1.2J
6: tail skin grouting	U = 1.25(w + G)
7: secondary grouting	U = 1.25(w + G)
8: earth pressure and groundwater load	U = 1.25(w + WAp) + 1.35(EH + EV) +1.5 ES
9: longitudinal joint bursting	U = 1.25(w + WAp) + 1.35(EH + EV) +1.5 ES
10: additional distortion	U = 1.4Mdistortion

Note: w = self-weight; F = self-weight of segments positioned above; J = TBM jacking force; G = grout pressure; WAp = groundwater pressure; EV = vertical ground pressure; EH = horizontal ground pressure; ES = surcharge load; and Mdistortion = Additional distortion effect; d = dynamic shock factor

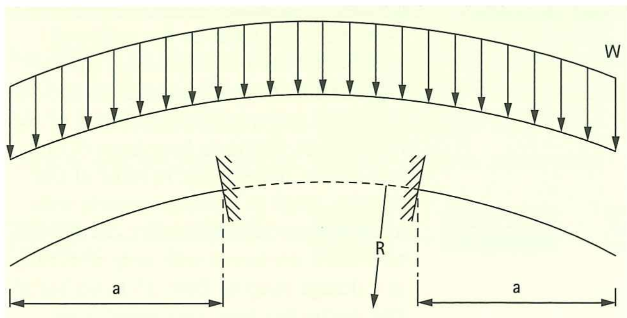
using specified post-crack residual tensile strength, σ_p (ACI 544.8R, 2016). The design approach of the ACI report is applied to a case of mid-size tunnel to illustrate the applicability of the proposed design procedures.

DESIGN OF SEGMENTS FOR ULS

The design engineer should use the Strength Design method introduced by ACI 318 (2014) by implementing combination of factored loads and reduced strengths to design precast concrete tunnel segments for ultimate limit state (ULS). ULS, which is a state associated with the collapse or structural failure of tunnel linings, is discussed in this section. The current practice in the tunnel industry is to design these elements for the following load cases, which occur during segment production, transportation, installation, and service conditions:

- Production and transient stages
  - Load Case 1: segment stripping
  - Load Case 2: segment storage
  - Load Case 3: segment transportation
  - Load Case 4: segment handling
- Construction stages
  - Load Case 5: TBM thrust jack forces
  - Load Case 6: tail skin back grouting pressure
  - Load Case 7: localised back grouting pressure
- Final service stages
  - Load Case 8: earth pressure, groundwater, and surcharge
  - Load Case 9: longitudinal joint bursting
  - Load Case 10: additional distortion
  - Load Case 11: other (e.g., earthquake, fire and explosion)

Note that during the construction phase, designers may need to take into account other considerations, such as stresses due to gasket compression force, connecting dowels or bicones, vacuum erection shear cup and ring build imperfections. In the strength design procedure or ULS, the required strength (U) is expressed in terms of factored loads shown in Table 1. For load cases not covered by ACI 318 such as load cases 8 and 9, ACI 544 committee recommends using load factors and load combinations from AASHTO DCRT-1. The resulting axial forces, bending moments, and shear forces are used to design concrete strength and reinforcement. ACI 544 committee recommends a strength reduction factor of 0.70 for flexure, compression, and shear, and a strength reduction factor of 0.65 for bearing actions. The design procedure starts with selecting an appropriate geometry including selecting thickness, width and length of segments with respect to the size and loadings of the tunnel, followed by specifying compressive strength of concrete and reinforcement. Considering strength reduction factors, design strength of segments is compared with required strength, or otherwise improved.



***Top:** Stripping segments from the forms in manufacturing plant **Above:** Figure 1, forces acting on segments*

Production and transient stages

Load case of segment stripping represents the effect of lifting systems on stripping precast concrete segments from the forms in the segment manufacturing plant. Figure 1 shows the stripping phase that is modelled by two cantilever beams loaded under their own self-weights (w). Segment radius and cantilever length of segment subjected to bending are represented by R and a, respectively. The design is performed with regard to the specified strength when segments are stripped (i.e., three to four hours after casting). As shown in Figure 1, the self-weight (w) is the only force acting on the segment, and therefore, the applied load factor in ULS is 1.4 per ACI 318 (2014). Note that ACI 544 does not consider a dynamic shock factor for the load case of stripping due to high quality control of the machines and equipment used in manufacturing plant. Designers can use recommendations of PCI Design Handbook to consider dynamic shock factor for this load case, in case high quality procedure is not insured.

Segment stripping is followed by segment storage phase in the stack yard where segments are stacked to gain specified strength before transportation to the construction site. Segments comprising a full ring are piled up within one stack. Designers provide the distance between the stack supports considering an eccentricity of e = 0.1m between the locations of the stacks support for the bottom segment and the supports of above segments. A simply supported beam loaded as in Figures 2a and 2b represent this load case. As shown in the figure, dead weight of segments positioned above (F) is acting on designed segment in addition to its self-weight (w). Therefore, corresponding load combination is 1.4 w + 1.4 F per ACI 318 (2014).

During the segment transportation phase, precast segments stored in the stack yard are transported to construction site and TBM trailing gear. Segments may encounter dynamic shock loads during this phase and usually half of the segments of each ring are transported in one car. Wood blocks provide supports for the segments. An eccentricity of 0.1m is recommended for design. Similar to segment storage phase, simply supported beams represent the load case of transportation with dead weight of segments positioned above (F) and self-weight (w) as the acting loads on designed segment. In addition to load combination of 1.4 w + 1.4 F per ACI 318 (2014), a dynamic shock factor of 2.0 is applied to the forces for the transportation phase.

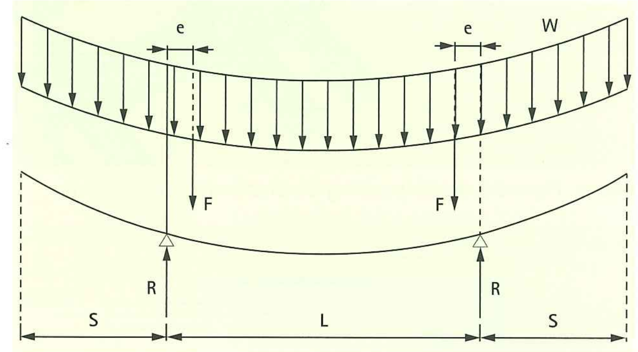
Segment handling from stack yard to trucks or rail cars is carried out by specially designed lifting devices or vacuum lifters. Inside the TBM, segment handling is usually carried out using vacuum lifters while other methods may be used occasionally. This load case is simulated similarly to segment stripping shown in Figure 1. Self-weight (w) is the only force acting on segments and therefore, a dead load factor of 1.4 in ULS per ACI 318 (2014) and a dynamic shock factor (d) of 2.0 are recommended for design. Maximum bending moment and shear forces developed during the above-mentioned stages are used for design checks.

Construction stages

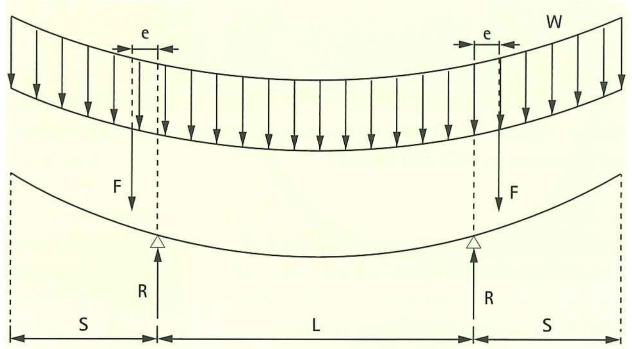
The first load case during construction stage is TBM thrust jack forces. After assembly of a ring, the TBM moves forward, as shown in Figure 3, by pushing its jacks on bearing pads placed on the circumferential joints of the newest assembled ring. This action results in development of high compression stresses under the pads, as well as bursting tensile stresses deep in the segment and spalling tensile forces between the pads. Maximum thrust force for each jack pair (J) is obtained by dividing maximum total thrust of TBM, if known, over the number of jack pairs.

In another approach, jack thrust forces on each pad (J) are estimated as the sum of forces required for boring into the rock or acting pressure on cutting face due to earth or slurry pressure, plus friction resistance between the shield surface and the ground, and hauling resistance of trailing gears, divided over the number of jack pads. Since TBM thrust jack forces (J) are the only forces acting on segment

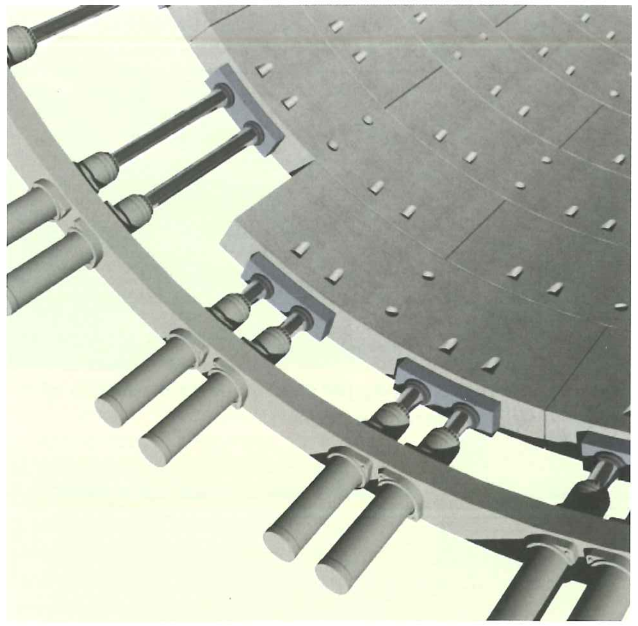
***Above:** Segments stacking for storage and schematics of forces acting on bottom segment*



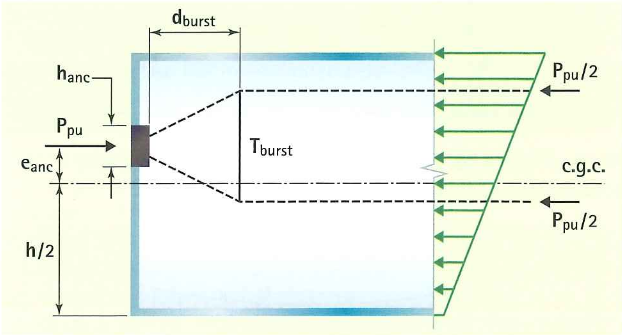
***Above:** Figure 2a, Segments stacking for storage and schematics of forces acting on bottom segment*



***Above:** Figure 2b, Another representation of segments stacking for storage*



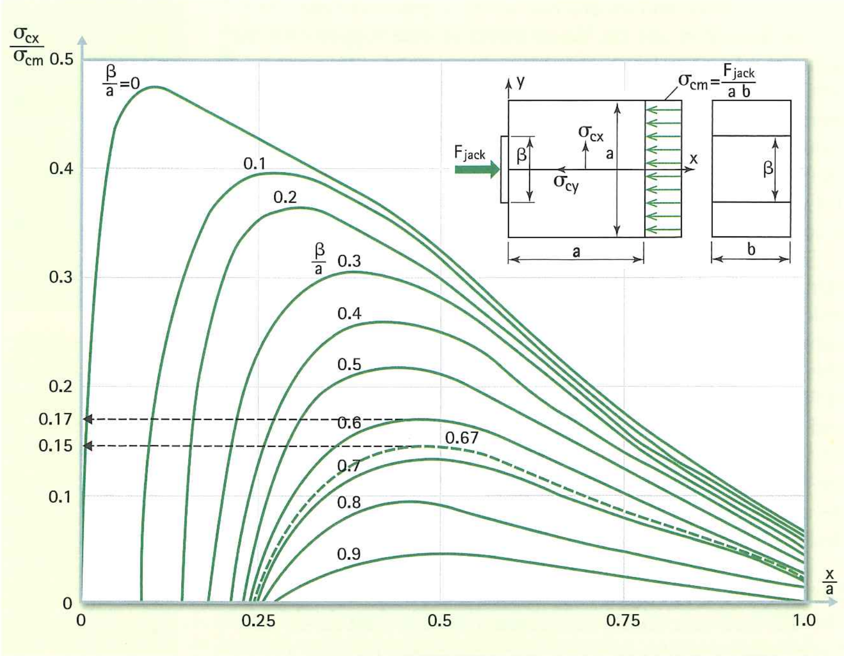
Above: Figure 3, jacks pushing on circumferential joints



Above: Figure 3b, Bursting tensile forces and corresponding parameters in ACI 318 (2014)

joints, no load combination is defined. It is recommended to apply a load factor of 1.2 on jack forces applied on each pad to take into account the higher machine thrust effect on the convex side of the curve comparing to the concave side when negotiating sharp curves of alignment. Note that in the case of the jacking force calculation based on face pressure and skin friction, the load factor for jacking force should be similar to the load factors for the face pressure and skin friction calculation. Different design methods include simplified equations of ACI 318 (2014), and DAUB (2013) presented by Equations (1) and (2), Iyengar (1962) diagram, and finite element (FE) simulations.

Where T_{burst} and d_{burst} are bursting force and centroidal distance of bursting force from face of section as shown in Figure 3b, P_{pu} is the jacking force applied on each jack pad, h_{anc} is the length of contact zone between jack shoes and the segment face, h is the depth of cross section, and e_{anc} is the eccentricity of jack



Above: Figure 4a, Lyengar (1962) diagram for determining bursting tensile stresses (Groeneweg 2007)

ACI 318: $T_{burst} = 0.25P_{pu}\left(1 - \frac{h_{anc}}{h}\right)$

$d_{burst} = 0.5\,(h - 2e_{anc})$

DA UB: $T_{burst} = 0.25P_{pu}\left(1 - \frac{h_{anc}}{h - 2e_{anc}}\right)$

$d_{burst} = 0.4\,(h - 2e_{anc})$

Above left: Figure 1, equation
Above right: Figure 2, equation

pads with respect to the centroid of cross section. If no specific value has been provided for e_{anc}, then the eccentricity of the jacking forces is generally considered to be 30mm. Note that this eccentricity 30mm should be compared with actual segment joint geometry, considering gasket grove and the proposed jacking shoe details and position.

High compressive stress is developed under the jacking pads due to the TBM thrust jacking forces. This compressive stress, considering al as the transverse length of the contact zone between jack shoes and the segment face, can be estimated using Equation (3).

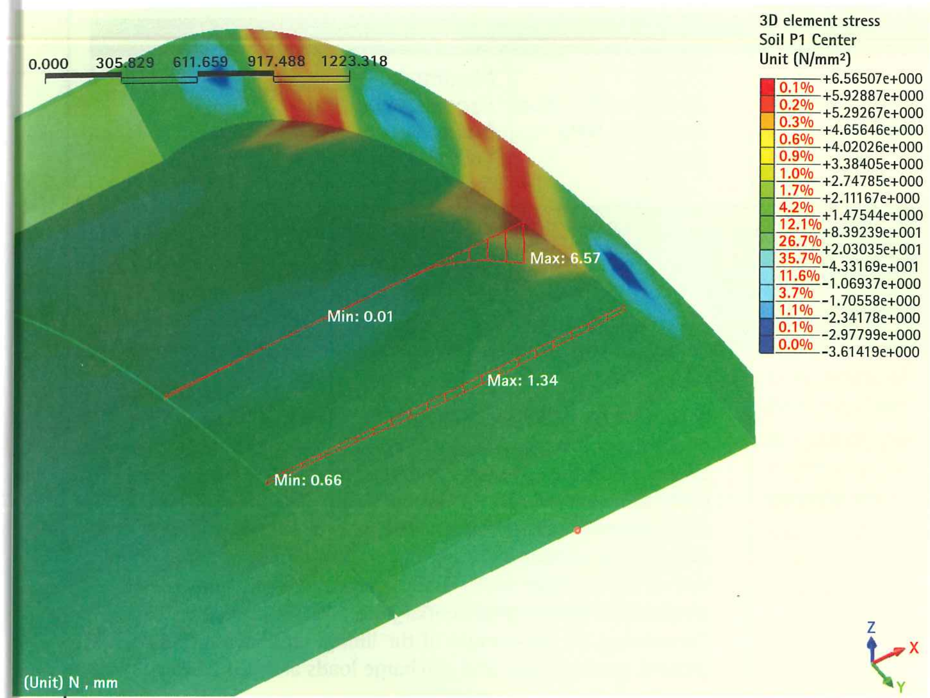
$$\sigma_{cj} = \frac{P_{pu}}{a_l h_{anc}}$$

Above: Figure 3, equation

Because only part of the circumferential segment face is actually in contact with the pads, the allowable compressive stresses (f'_c) can be factored to account for the strength of a partially pressurised surface. ACI 318 (2014) specifies the formula used for designing the bearing strength of concrete with a partially loaded segment face. DAUB (2013) recommends a similar formula that is specifically used for designing tunnel segment faces:

$$f'_{co} = 0.85 f'_c \sqrt{\frac{a_t\,(h - 2e_{anc})}{a_l h_{anc}}}$$

Above: Figure 4, equation



Above: Figure 4b, finite element model showing typical bursting and spalling tensile stresses developed in segments due to TBM thrust jack forces (Bakhshi and Nasri, 2013)

where f'_{co} is compressive strength of partially loaded surface and a_t is transverse length of stress distribution zone at the centreline of segment under thrust jacks.

In another approach, using the Iyengar diagram shown in Figure 4a, tensile stresses are obtained considering β and b as the dimensions of the loaded surfaces, a as the dimension of stresses spreading surface inside the segment, and σ_{cm} (F/ab) as a fraction of the fully spread compressive stress.

Figure 4b, on the other hand, shows typical results of a 3D FE simulation of the effect of jack thrust forces on circumferential joints of a large-diameter tunnel. As shown in Figure 4b, in addition to the bursting stresses under the jacking pads, spalling stresses develop in the areas between the jacking pads due to the concentration of the jacking forces. Reinforcement is provided to control these bursting and spalling stresses.

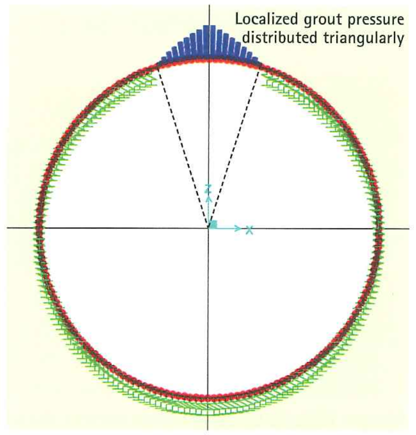
The load case of tail void grouting presents backfill grouting or filling the annular space with semi-liquid grouts, which is required in order to control and restrict settlement at the surface and to securely lock the lining ring in position. Grout pressure has to be limited to a minimum value that is slightly higher than the water pressure, and a maximum value that is less than the overburden pressure. For the case of tail void grouting, vertical gradient of grout pressure is calculated by taking the equilibrium between the upward components of total grout pressure, lining deadweight and tangential component of grout shear strength (Groeneweg 2007). This load case is modelled by applying radial pressures increasing linearly from the crown to the invert of tunnel. Self-weight (w) and grouting pressure (G) are the acting loads on the lining at this phase, and a therefore, a load combination of 1.25 DC + 1.25 G needs to be applied in ULS following the AASHTO (2010) recommendation in the absence of an ACI 318 recommendation for this load case.

In the case of localised backfilling, radial injection through holes provided in the segments is performed where annular gaps exist between the lining extrados and excavation profile after tail grouting. The ITA WG2 (2000) approach is used for simulation of localised triangularly distributed backfilling pressure. As shown in Figure 5a, the lining is modelled as a 2D solid ring with a reduced flexural rigidity due to segment joints, and the interaction between the lining and surrounding ground or primary hardened grout is modelled by radial springs. Using a structural analysis package, bending moments and axial forces due to the grouting load cases are determined and checked against segment strength.

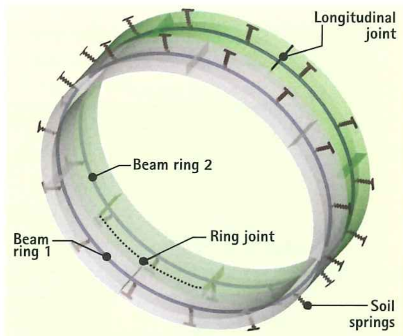
Final service stages

The loading in the final service stage is represented by the long-term interaction of the lining with the ground and groundwater pressure, as well as other factors specific to an individual tunnel, e.g., additional distortion, earthquake, fire, explosion, and breakouts.

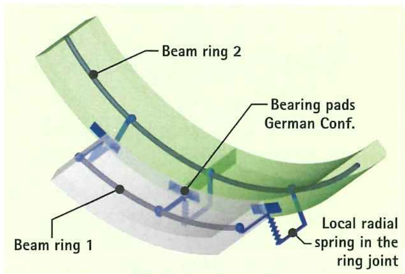
Longitudinal joint bursting load due to force transfer in a reduced cross section



Right: Figure 5a, Modeling localized grouting pressure applied over 1/10th of lining perimeter



Right: Figure 5b, Double ring Beam-Spring model with radial soil springs, together with longitudinal and ring springs representing segment joints



Right: Figure 5c, Scheme of the ring joint (ACI 544.7R 2016) because of gasket and stress relief grooves is another critical load case in the final service stage. Due to similarity to the effect of thrust jack forces it is not discussed further as similar analysis and design methods are applicable to this particular load case.

Precast concrete segments as final lining system withstand different loadings in the service stage including ground (vertical and horizontal) loads, groundwater pressure, dead weight, surcharge and ground reaction loads. As presented in Table 1, in the absence of an ACI 318 recommendation for this load case, load factors and load combinations from AASHTO (2010) are used to compute the forces.

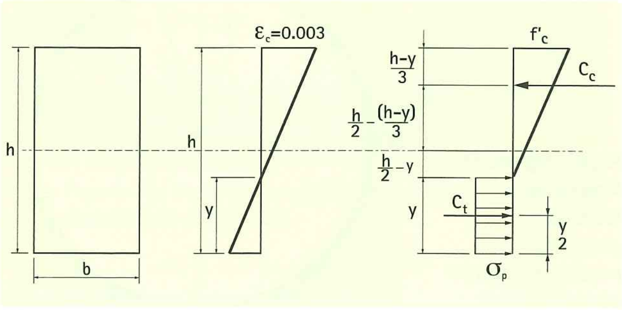
Effect of ground, groundwater and surcharge loads as the major final service stage load case is analysed using elastic equations, beam-spring models, FEM and Discrete Element Methods (DEM).

Beam-spring models are the most conventional methods. As shown in Figure 5b and 5c, a so-called two-and-a-half-dimensional, multiple-hinged, segmented, double-ring beam spring has been used to model the reduction of bending rigidity and the effects from a staggered geometry. This manipulation is achieved by modelling the segments as curved beams, flat longitudinal joints as rotational springs (Janßen joints [Groeneweg, 2007]), and circumferential joints as shear springs. Two rings are used to evaluate the coupling effects; however, with this method, only half of the segment width is considered from one ring for the longitudinal and circumferential joint zone of influence. Considering the self-weight of the lining, and distributing the ground, groundwater, and surcharge loads along the beam, member forces can be calculated using a conventional structural analysis package.

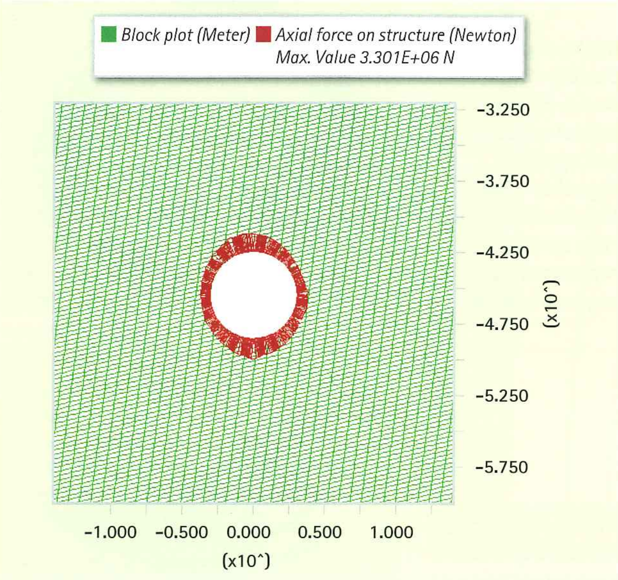
Other acceptable methods of analysis include Muir Wood (1975) continuum model with discussion from Curtis (1976), Duddeck and Erdmann (1982) and an empirical method based on tunnel distortion ratios (Sinha, 1989).

Table 2. Segment design checks for production and transitional stages

Phase	Specified Residual Strength, MPa (psi)	Maximum Factored Bending Moment, kNm/m (kipf-ft/ft)	Resisting Bending Moment, kNm/m (kipf-ft/ft)
Stripping	2.5 (360)	5.04 (1.13)	26.25 (5.91)
Storage	2.5 (360)	18.01 (4.05)	26.25 (5.91)
Transportation	4.0 (580)	20.80 (4.68)	42.00 (9.44)
Handling	4.0 (580)	10.08 (2.26)	42.00 (9.44)



Above: Figure 6, Strain and stress distributions through the section as part of it undergoes tension



Above: Figure 7a, DEM model

DESIGN EXAMPLE

An example for design of a mid-size TBM tunnel lining with precast FRC segments is presented. It is assumed that internal diameter of the segmental ring is D_i = 5.5m, and the ring composed of five large segments and one key segment (one-third of the size of large segments). Width, thickness and curved length at centreline of the large segments are 1.5m, 0.3m and 3.4m, respectively. A stress-strain diagram according to ACI 544.8R (2016) is adopted. Key design parameters for aforementioned load cases are the specified residual tensile or residual flexural strength (σp or f^{D}_{150}) and specified compressive strength (f'_c). A scale factor of 0.34 is considered to convert f^{D}_{150} to σp.

Designed demoulding and 28-day f^{D}_{150} strengths are 2.5 MPa (360 psi) and 4 MPa (580 psi), respectively. Specified compressive strengths are 15 MPa (2,175 psi) for demoulding and 45 MPa (6,525 psi) for 28-day FRC segments. As shown in Figure 6, capacity of FRC segments are calculated based on equilibrium conditions assuming a post-crack plastic behaviour in the tension zone. First crack flexural strength (f_1) is assumed as 4 MPa (580 psi). Design checks for the production and transitional loads are shown in Table 2. The tunnel is excavated in jointed rock. Two-dimensional DEM model shown in Figure 7a is used for calculation of tunnel lining forces in three different geological reaches defined along the alignment. Design checks for the load case of the ground and groundwater pressure is shown in Figure 7b. A TBM with maximum total thrust of 5,620 kips (25,000 kN) applied on 16 jack pairs is assumed for this project. Maximum thrust forces on each pair is therefore 351 kips (1.562 MN). The length and width of the contact area between the jack pads and segments, considering a maximum eccentricity of e = 0.025m, are al = 0.87m and h_{anc} = 0.2m, respectively.

Dimensions of fully spread stresses are at = 11.1ft/3 = 3.7ft (1.13m) and h = 12in (0.3m) in tangential and radial directions, respectively. Conforming to simplified equations of ACI 318 (2014), bursting force (T_{burst}) and its centroidal distance from the face of section (d_{burst}) in radial and tangential directions are:

Maximum bursting stresses developed in radial and transverse directions with a ULS load factor of 1.2 are

Tangential direction:

$$d_{burst} = 0.5(a_t - 2e) = 0.5(3.7 - 2 \times 1/12) = 1.77\ ft\ (0.54m)$$

$$T_{burst} = 0.25P_{pu}\left(1 - \frac{a_l}{a_t - 2e}\right) = 0.25 \times 351 \times \left(1 - \frac{34}{3.53 \times 12}\right) = 17.32\ kipf\ (0.077\ MN)$$

Radial direction:

$$d_{burst} = 0.5(h_t - 2e_{anc}) = 0.5\,(12 - 2 \times 1) = 5\ in\ (0.125m)$$

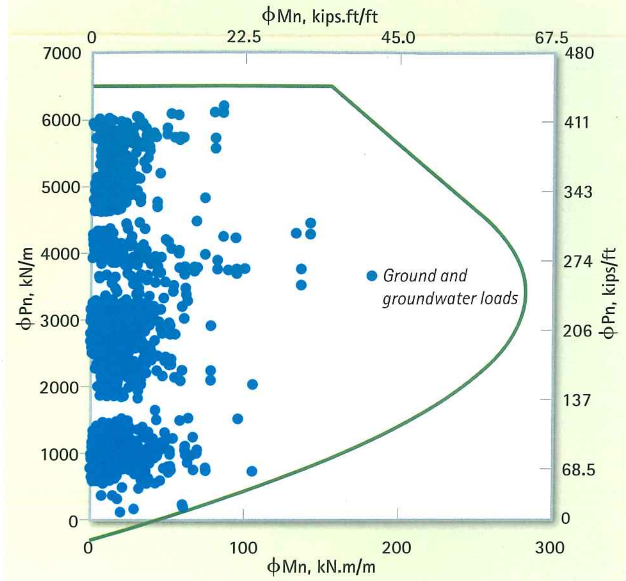
$$T_{burst} = 0.25P_{pu}\left(1 - \frac{h_{anc}}{h - 2e_{anc}}\right) = 0.25 \times 351 \times \left(1 - \frac{8}{12 - 2 \times 1}\right) = 17.55\ kipf\ (0.078\ MN)$$

Tangential direction:

$$\sigma_p = \frac{1.2T_{burst}}{\phi h_{anc}\, d_{burst}} =$$

Above: Figure 5, equation

These stresses are less than 28-day specified residual tensile strength of FRC segment as σ_p = 0.34 f^{D}_{150} = 0.34(580) = 197 psi (1.36 MPa), and the design is valid for load case of TBM thrust jack forces.



Above: Figure 7b, design checks for the load case of ground and groundwater pressure

CONCLUSIONS

Regardless of the advantages of FRC, its use in tunnel segments has been limited due to lack of recommendations and guidelines. This paper briefly explains the design concepts of a new ACI report that is the first design guideline on FRC segments. Presented design procedures include design for production and transient, construction and final service stages. Application of the design approach to case study of a mid-size tunnel in jointed rock indicates that the use of fibres can lead to elimination of steel bars.

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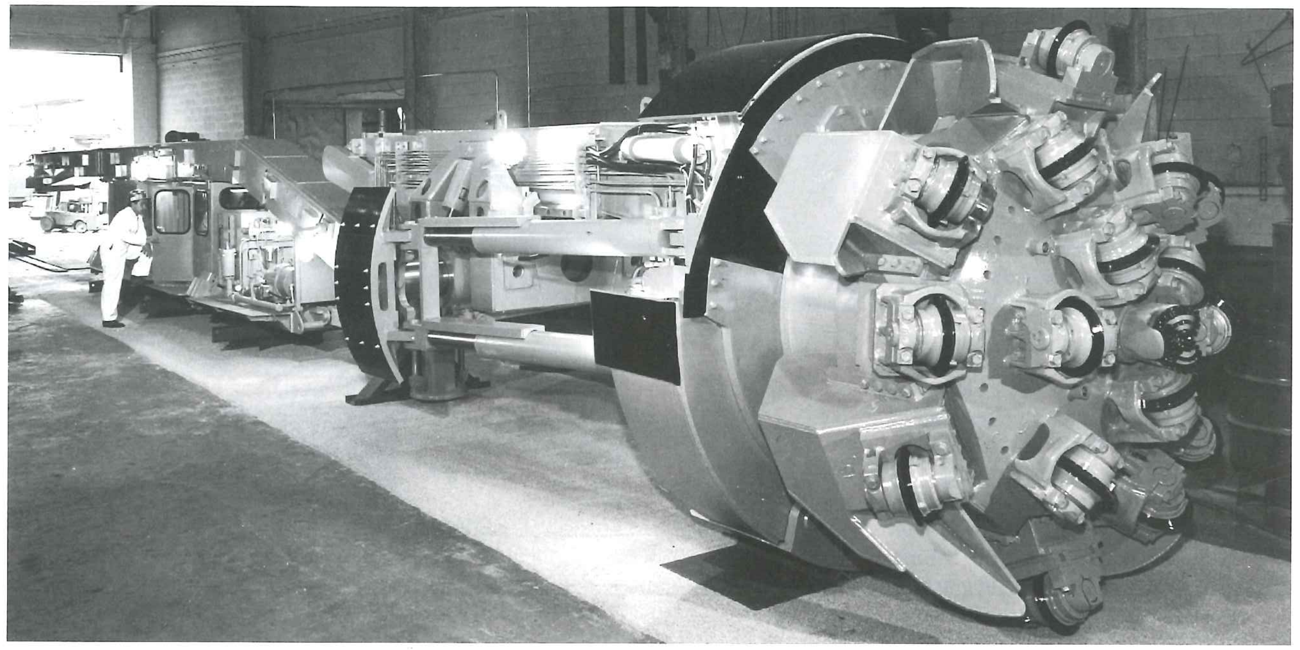
JUST LIKE NEW

In the TBM world, multi-use machines offer time and cost savings



Above: McNally Construction Inc.'s workhorse TBM— a 2.7m diameter Robbins main beam still in good working condition - was originally manufactured in 1968, making it almost 50 years old (pictured in its original condition for a project in Tasmania)

Desiree Willis
The Robbins technical writer has covered a range of topics for *Tunnels and Tunnelling*

SWISS CONTRACTOR MARTI TUNNELBAU'S 4.4m diameter Robbins main beam TBM, affectionately nicknamed "The Old Lady", has been a big competitive advantage. The TBM was originally built in 2002 for the Upper Diamond Fork project in Salt Lake City, Utah, USA, before being used on the McCormick Place tunnel in Chicago, Illinois, USA. The machine was purchased by Marti for the Bracons tunnel in Spain, excavated from 2006 to 2008, and they have retained it ever since. "For us the value of owning this machine is in modifying it ourselves, having a good knowledge of the whole system and a staff experienced in working on the machine. It helps us to be faster during assembly and startup of the machine on site," says Thomas Güggi, technical director for Marti.

Güggi estimates that the savings on various projects – depending on the amount of specialisation – can be substantial as compared to buying a new machine every time. "If we count an amortisation time for the TBM of up to 20km tunnelling or five projects we can save (including all refurbishment costs) at least 30 per cent compared to purchasing a new machine - if we can keep the back-up with minimal changes." He adds that this savings is for smaller diameter machines of perhaps 5m or less that are not undergoing a diameter change. Even with that, there are some cost savings with rebuilds of larger machines and diameter changes (perhaps 5 per cent). And there are time savings all around, no matter the diameter. "The savings on mobilisation time is very important. Refurbishment can be done in a few months (as few as three), saving us five months as compared to a new machine."

Marti's machine has been used on two recent projects since the Bracons tunnel – the Milchbuck Safety Gallery in Switzerland in 2012, for which the TBM underwent a major diameter change from 4.4 to 4.15m and required a new back-up system—and most recently Sisto Sachseln, another Swiss tunnel that required a diameter adjustment to 4.2m and some upgrading of electrical, ventilation, and dust extraction systems. Altogether, the machine has been used on five tunnels thus far totalling 12.3km (9.7 of which were bored by Marti). While the machine does not have a current project, Güggi sees few limitations: "It will surely be able to dig more jobs, at least 10km or more.

Below: ***In the case of a project, a new machine might be the correct solution if a convertible concept like the Crossover TBM is required. The 8m diameter Crossover XRE TBM for Australia's Grosvenor Decline Tunnels is pictured during its onsite first time assembly***

Limiting factors could be demands by law or new normative demands for TBM capabilities. There may be some limits on certain components, such as electrical or hydraulic systems, but we expect the steel structure will last for many years"

QUANTIFYING TIME AND COST SAVINGS

Time and cost savings for a rebuilt machine can be highly variable, depending on the extent of the rebuild and the number of projects on which the machine is used. But there is general agreement that under the right conditions, the savings can be significant. "If we built a 3m diameter main beam machine, and we do a rebuild at the same diameter with many of the same components, that will save a lot more than rebuilding that same 3m machine as a 4m machine with a brand new back-up system," says Doug Harding, Robbins VP-sales.

Canada's McNally Construction is a good example of just how much savings a rebuilt TBM (or three) can provide. The company owns four Robbins machines, including one of the oldest TBMs still in operation--a 2.7m diameter main beam TBM originally built in 1968. The machine was first used for a hydroelectric tunnel in Tasmania, and was purchased by McNally in 1972 for use on multiple sewer tunnels in Toronto and Ottawa.

"Of the three that we originally purchased (a 3.6m, a 2.9m, and a 2.7m diameter machine) they have completed over 50km of tunnels on over 12 projects. We custom-modified the cut size each time by adjusting cutters and buckets to suit the requirements of the owner," says Steve Skelhorn, project sponsor for McNally Construction. Over the years, the company also added guidance systems, updated the hydraulics, added probe drilling capabilities and added foaming agent dust suppression systems, and more recently updated one of the TBMs to Class 1 Division 2.

"With refurbishment at the start of each project, these TBMs will continue indefinitely. Major components, such as bearings, cutterheads, grippers and hydraulics may all eventually need replacing but not necessarily at the same time," adds Skelhorn. As for the savings of using rebuilt machines vs. new ones for each project, he speaks from experience: "Savings during a rebuild is highly variable and can range from 75 per cent cheaper for a simple machine and a tunnel project with tried and tested ground conditions, to around 20 per cent cheaper for a project with more complex requirements (a high-pressure EPB for example)."

For McNally Construction, the advantages of rebuilt machines aren't just in the costs. Skelhorn states that the time savings of using a rebuilt machine can be six months or more (as long as the TBM truly fits the project specifications and is not a compromise, and major changes aren't required).

The other benefit is in owning the machine itself: "Familiarity of the TBM is a big plus: operators and maintenance crews are familiar with the equipment, which can greatly improve performance during the initial learning curve."

On the importance of maintenance

It should be emphasised that other factors affect the frequency and cost of rebuilds, such as maintenance. "Maintenance is an important factor to ensure the multiple use of a TBM," says Güggi. "Staff should know the machine very well and treat it well. Systematic maintenance and control will avoid serious and costly repairs and helps keeping refurbishment costs low."

For McNally, maintenance has a direct effect on rebuild costs later on. "Maintenance is essential for performance on a particular project. It does not really reduce the machine's ability to do multiple projects, but a lack of maintenance can definitely affect the costs of refurbishment."

Storage between projects is a key part of that maintenance. Güggi explains, "We conserve the structure using a kind of anticorrosive oil spray. The assembled TBM itself and all critical components we store in a warehouse - the cutterhead we let turn every month and the main bearing is filled with oil."

At McNally, storage is equally critical: "Typically, TBM systems are drained (specifically water systems, which are critical in cold climate). Cable ends are all

Right: ***Marti Tunnelbau AG's 4.4m diameter TBM has been used on 9.7km of tunnel since its use on the Bracons tunnel (pictured) in 2006, and on 12.3km of tunnel since its original manufacture in 2001***

Below: ***McNally Construction's 2.7m diameter main beam TBM is one of the longest running TBMs still operating in the world. Purchased as a rebuilt machine in the 1970s, the TBM along with two other rebuilt Robbins machines have excavated 50km of tunnel for the company over the years***

waterproofed and all hydraulic systems are capped. Critical electronic components are removed and stored inside. The TBM and support gear are then shrink-wrapped – similar to boat wrapping protection," says Skelhorn.

THE ART OF THE REBUILD

The rebuilding of TBMs – both the process and the standardisation of rebuilds – has become a focus for the industry as more projects with multiple machine requirements and short time frames are being proposed. The focus has been further highlighted by Itatech, a technology-focused committee for the International Tunneling Association that has recently produced guidelines on rebuilds of machinery for mechanised tunnel excavation in 2015.

In general, Robbins' experience with rebuilding machines has yielded some key insights. As long as the TBM is well-maintained, there will be jobs it can bore economically. Optimal TBM refurbishment on a used machine requires a broad knowledge of the project conditions, and there are some limitations:

- Machine diameter can be decreased within the limits set by free movement of the grippers and side/roof supports
- Machine diameter can be increased subject to the structural integrity of the machine and the power/thrust capabilities
- Propel force can be increased only to the level supported by the grippers' thrust reaction force
- Cutterhead power must be adequate to sustain the propel force in the given rock, but cannot be increased beyond the capacity of the final drive ring gear and pinions
- Cutterhead speed increases must not exceed the centrifugal limits of muck handling or the maximum rotational speed of the gauge cutters

Increasing the power of the TBM is one way to make the design more robust for a longer equipment life. Strong designs have been developed in recent years, including Robbins High Performance (HP) TBMs, and used in a number of hard rock tunnels. These TBMs are designed with a greater strength of core structure and final drive components. They can be used over a much wider range of diameters, whereas older machines (from the 1970s and 80s) are typically limited to a range of less than 1m of diameter change plus or minus their original size. They have the capability of operating over a broad range. For example, a 4.9m TBM can be refurbished between 4.3m and 7.2m diameters—a range of 2.9m. Main bearing designs have allowed for greater flexibility, evolving from a two-row tapered roller bearing to the three-axis, three-row cylindrical roller bearing used today. This configuration gives a much higher axial thrust capacity for the same bearing diameter and far greater life in terms of operating hours or revolutions.

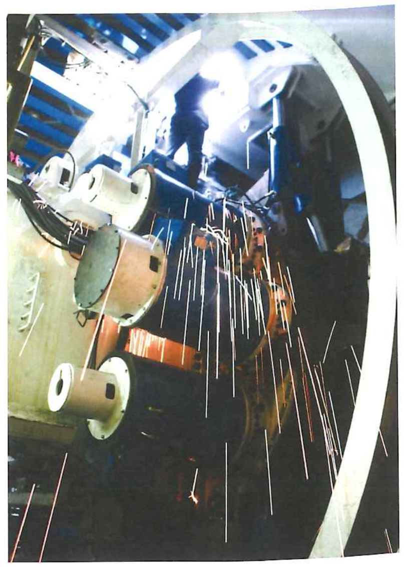
Overall, what determines how long a TBM will last is a function of the fundamental design, such as the thrust and gripper load path through the machine and the robustness of the core structure. On older model TBMs, the ring gear and pinions can be strengthened, and larger motors can be added. With sufficient core structure strength, it is also possible to increase the thrust capacity. The limitation is the capacity of the gripper cylinder to handle the increased power and thrust. Once replacement of the gripper cylinder and carrier are required, TBM modification costs are generally considered uneconomic.

TO ACCESSORISE OR NOT TO ACCESSORISE

As Skelhorn says, "This is one of the great debates, with the KISS mindset ('keep it simple stupid') against the 'We must have all the bells and whistles' mindset. Obviously fewer features means there is less to go wrong, but on the other hand, more features provide protections and feedbacks allowing improvements to be made."

Modern systems on TBMs, it can be argued, allow for better monitoring of the machine and therefore better maintenance and operation. Such systems could therefore extend equipment life in the long run. The capabilities of a modern machine, says Harding, are vast: "All the modern machines within the last 15 years have had VFDs so that is not necessarily a new component. Major electrical systems like VFDs have been modernised to be very reliable. PLCs,

Below: ***Most recently used on the Swiss tunnel Sisto Sachseln in 2015 (pictured), Marti carefully maintains the TBM between projects using anticorrosive spray and by keeping components such as the cutterhead and main bearing lubricated and in working order***



Above: Robbins said its TBMs are built with a long life in mind: components meet 10,000 design life standards

controls, and monitoring have been advancing in recent years. We can monitor oil, vibration, loading, and many other machine parameters to have a better idea of the current state the machine is in."

Skelhorn agrees on the advantages of monitoring: "Generally speaking the modern electronic systems are driven by client-provided specifications and do provide the advantage of being able to monitor in real-time TBM performance as well as provide good tools for post tunnelling analysis. In my view I would rather have a machine with all the features, however these must be robust and easily understandable by the maintenance crews. In other words, the systems should be reliable and enhance the mining, not hinder it with bugs and faults. It is also important to establish early on what systems are really required for improving the performance, versus those systems which are considered nice to have."

Harding is also aware of needed vs. 'nice to have' features and adds: "There are many ways to define 'bells and whistles'. If a feature is needed, whether it's increased thrust, a tapered shield, water control, or other custom design then it is not an extra. In our opinion a probe and grout drill are a cheap form of 'risk insurance' to detect problems ahead of the machine. On the other side of things, fully interchangeable components can be costly if you don't need them (as in a screw conveyor to belt conveyor conversion), so these types of features should be based on a detailed GBR."

On the other side of things, Skelhorn says that with more features "refurbishment is more involved and requires the use of specialists to supplement the TBM mechanics and electricians used on the simpler machines." For Güggi, a simple machine is ideal but perhaps not always practical: "To have a simple machine would be great – but the demands of contractors/safety and health/law almost exclude such machines in most cases. New technical demands are forcing us to have PLC systems on most projects. But, either way I think we have good experience in these matters and we can build reliable systems."

IN CONCLUSION: REBUILT OR NEW?

Like so many things in the tunnelling industry, the question of "rebuilt or new" is not a simple one. "Many owners now specify a new TBM for projects. This is on the assumption that new TBMs will be more reliable. In my experience this is not always the case. Refurbished machines are tried and tested and have all the bugs worked out. However this must be weighed against the overall requirements for the TBM being able to cope with the ground," says Skelhorn. He gives an example of just how complex it can be: "There was a project in Europe in the mid-1990s where two EPB tunnels were being excavated through complex ground with existing TBMs. Water pressures were over and above those the machines had seen before and these early EPB machines had no discs, no foam systems and a centre-mounted screw conveyor. EPB control was difficult to say the least and progress was slow – around 4m per shift. To accelerate the schedule, a new custom-built TBM was purchased, specifically designed to deal with the conditions. This TBM achieved a massive increase in production with a best shift production of 30m."

At Robbins, new machines are often required for unique conditions. "In the case of a project, a new machine might be the correct solution if you need a specialised concept, have a unique geological condition or a convertible concept like the crossover TBM," said Harding. "A very long tunnel in very hard rock is another example where a new machine might be better. Robbins supplies new TBMs for about 50 per cent of its projects. "For the other projects, of about 6,000m long or less, in relatively known geology, a rebuild is appropriate. The advantage is in cost savings and delivery time. It is also helpful when there is data from a previous project in a given geology that supports the design of the rebuilt machine so its performance is known. For example projects in Cleveland Shale, Texas Chalk, Chicago limestone, and others. Metro projects where tunnels are fairly short, and geology is known, can be another condition where a metro-sized EPB can be used over and over again because of short tunnel lengths."

A point in favour of new TBMs is one that Skelhorn indicates as not often considered: "Most contracts we are working on are design-bid-build, and we have to take into account life cycle costs. An existing TBM will dictate tunnel diameter and may reduce construction cost initially; however, purchasing a new TBM allows the size – and in the case of segmentally lined tunnels, the final lining design--to be customised.

"This can lead to an increased hydraulic performance, which over the life cycle of the tunnel can greatly outweigh any additional costs."

The true answer of "new or rebuilt" is thus dependent on a number of project conditions and requirements. Harding says that Robbins works to reduce the time gap between new and rebuilt machines, and between standard and customised machines, but of course simpler machines and rebuilt machines will be built more quickly.

"We can build a brand new, fully customised crossover type machine in 11 to 12 months. We can also build a standard metro-sized EPB in nine to 10 months. One is standard, one is custom—it is all dependent on the customer needs."

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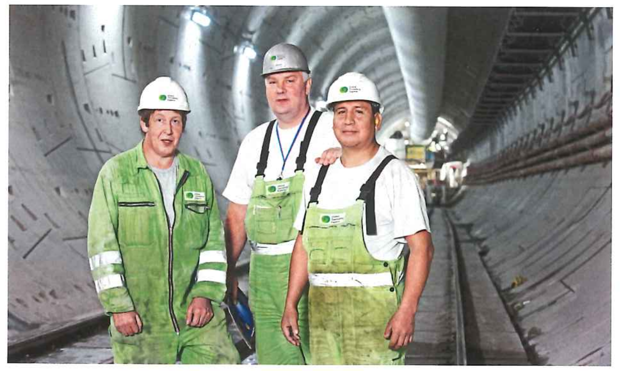

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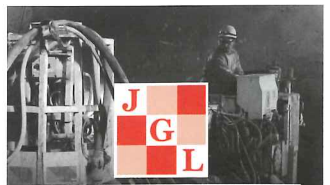

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2017

Underground Infrastructure of Urban Areas
24-26 October 2017
Wroclaw, Poland
This ITA endorsed conference is being organised by Wroclaw University and the Polish Tunnelling Group. The conference will cover the theme: "discussion on problems related to underground Infrastructure".
www.pbp-ita.pl/.org

16th Australasian Tunnelling Conference
30 October-1 November 2017
Sydney, Australia
ATS 2017 is expected to build on the 2014 show and have over 400 attendees, 80 peer-reviewed papers and 50 exhibitors. Topics covered at the conference will include: Urban Planning, Project Development and Project Delivery; Construction Methodologies; Ground and Ground Support; Systems, Operation and Maintenance; Urban Design and Aesthetic; and also Digital Tunnel and Data.
www.ats2017.com.au

TBM Digs
16-18 November 2017
Wuhan, China
Following the success of the first two TBM Digs events, the conference returns for the third time. This year it heads to the city of Wuhan in China's Hubei Province.
www.tbmdigs.org

British Tunnelling Society Underground Health and Safety Course
27-28 November 2017
London, UK
The British Tunnelling Society runs a two-day annual Underground Health and Safety Course. The course has been developed to focus exclusively on the underground environment. It aims to provide an introduction or enhance existing basic knowledge and develop an awareness of the particular health and safety challenges that working underground can pose. It is held at the Institution of Civil Engineers in London, booking is open.
www.britishtunnelling.org.uk

12th Iranian Tunnelling Conference: Tunnelling and Climate Change
27-29 November 2017
Tehran, Iran
The drop in total precipitation around the world, especially in the Middle East and Iran has resulted in rapid decline of water resources available to societies. The construction of water conveyance tunnels by transferring water form water-rich regions to arid regions can have a significant role in reducing consequences of this growing phenomenon. This event will focus on the role of tunnelling in mitigating the effects of climate change.
www.itc2017.ir

Stuva Expo 2017
6-7 December 2017
Stuttgart, Germany
The premier tunnelling event in Germany returns to Stuttgart in December. The 2015 event's trade fair accompanying the Stuva conference exceeded all expectations. With 1,850 conference delegates and more than 550 trade visitors, around 2,400 visited in 2015 and the 2017 event is expected to build on this.
www.stuva-expo.com/en/

2018

IFCEE 2018
6-10 March 2018
Orlando, Florida
The world's leading foundations congress and equipment expo will be a broad-based geotechnical/geoprofessional event with a focus on case histories, providing value to practitioners as well as to academia.
www.geoinstitute.org/event/2018-geo-congress/

NASTT No Dig 2018
25-29 March 2018
Palm Springs, USA
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www.nastt.org

World Tunnel Congress 2018
20-26 April 2018
Dubai, UAE
The World Tunnel Congress heads to the United Arab Emirastes in 2018, and demonstrates the rise of the Middle East to the centre stage of the global tunnelling market. The organisers invite you to experience true Arabian hospitality and enjoy Dubai, which claims to be the world's most cosmopolitan city.
www.uaesocietyofengineers.com

North American Tunnelling Conference
24-27 June 2018
Washington D.C., USA
The NAT is the premier biannual tunneling event for North America, bringing together the brightest minds in the tunneling industry.
www.natconference.com

11th International Conference on Geosynthetics
16-21 September 2018
Seoul, South Korea
The technical program will include a Giroud lecture, 5-6 plenary lectures (special lectures), 2-3 short courses and approximately 50 parallel sessions. It is expected to attract more than 1,000 experts from over 100 countries.
www.11icg-seoul.org

PIARC International Conference on Road Tunnel Operations and Safety
3-5 October 2018
Lyon, France
This World Road Association endorsed event comes amidst increasing interest in the emergence of new types of vehicles in the driving environment, and how tunnels will keep pace with continuing technological advances.
www.piarc.org

10th Asian Rock Mechanics Symposium
29 October-3 November 2018
Singapore
Asia is witnessing the greatest growth and demand in the world for infrastructure and resource development. According to Asian Development Bank, approximately US$8 trillion needs to be invested in overall national infrastructure before 2020, 68% of which is for new capacity. Certainly, rock mechanics and rock engineering will have a critical role to play in many of these infrastructure and resource development projects. The theme for ARMS 10 is "Rock Mechanics in Infrastructure and Resource Development".
www.arms10.org

2019

Bauma
8-14 April 2019
Munich, Germany
The largest construction trade show in the world returns to its traditional venue in Munich. Last held in 2016, a lot can be learned about the health of the construction industry from the mood at this enormous event.
www.bauma.de

World Tunnel Congress 2019
3-9 May 2019
Naples, Italy
The one tunneling event that is unrivaled in its international reach. The World Tunnel Congress is coming to Italy and tunnellers representing owners, contractors, engineers and suppliers will be exhibiting. The event is expected to attact as many as 600 technical papers, 250 exhibitors and up to 3,000 attendees.
www.facebook.com/events/1753343481565751/

ECSMGE 2019
3-9 May 2019
Reykjavik, Iceland
The Icelandic Geotechnical Society are pleased to welcome you to the XVII European Conference on Soil Mechanics and Geotechnical Engineering, held in the Icelandic capital. The theme of the conference is "Geotechnical Engineering, foundation of the future" and will embrace all aspects of geotechnics.
www.ecsmge-2019.com

World Road Congress
6-10 October 2019
Abu Dhabi, UAE
The World Road Congress will cover a number of areas, including Road policies, Environment, Economics, financing, Governance of authorities, Planning, Risk management and many more.
www.piarcabudhabi2019.org

British Tunnelling Society evening meetings

The BTS has a membership of over 814 individual and 266 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. In recent years, the BTS Young Members (BTSYM) group has also begun hosting its own events.

Risk Management in Tunnelling Projects
19 October 2017
Tunnelling is a risky business but the project teams undertaking such work have had a great range of successful tunnels completed to the satisfaction of tunnel users, whether rail passengers, car drivers or utility users. But there is always improvement to be had and dangers to watch for. This meeting will try and assist in an understanding of this and other subjects under the broad title of risk and delivered with the assistance of representatives from the insurance industry.
Speakers: Nigel Legge, Kevin Province, Bill Grose

Finsbury Park Squareworks
16 November 2017
A presentation on the Finsbury Park Station step-free access scheme for London Underground. This will include information on squareworks tunnelling, shaft sinking and undertrack crossings, all carried out from within a live station.
Speakers: Farid Achha, London Underground; John Elliott, Alan Auld Engineering; Menelaos Lydakis, C Spencer Group

Waterview Tunnel, New Zealand
14 December 2017
A Memorial Lecture in commemoration of the late Chris Parker (formerly Balfour Beatty International director and general manager, with responsibilities for both UK and International tunneling projects), and will include a brief tribute to Chris, by Mike McConnell. The Lecture will be given by Tom Parker (Chris's son) and colleagues, on the Waterview Connection in Auckland, which is the largest and most complex Road Project ever undertaken in NZ. The project includes twin tunnels, each three lanes wide, with an outside diameter of 14.41m, excavated under residential development, the Great North Road, and Auckland's western rail corridor.Tom will also provide a flavour of some of New Zealand's future major infrastructure projects.
Speakers: Tom Parker (Project Director) and Iain Simmons (Tunnelling Manager)

Tunnel Design Life of 120 years - Definition, Assessment and Improvement
18 January 2018
The first meeting of 2018 will focus on design life requirements of tunnels and how these are assessed by designers; and improvements and cost savings that can be made on projects when the concrete mixes are tested early on in the design stage.
Speakers: Charles Allen, Phil Bamforth, Jon Knights

Joint BTS/Minsouth Meeting: North Yorkshire Polyhalite Project
8 February 2018
Details to be confirmed. Attendees are reminded that this meeting takes place on the second Thursday of the month.
Speakers: Charles Allen, Phil Bamforth, Jon Knights

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

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