

INTERNATIONAL EDITION

November 2014

# Tunnels

AND TUNNELLING

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## REMEMBER THE FIFTH OF NOVEMBER

**I**N A couple of months it will be the 410th anniversary of the first attempt at the Gunpowder Treason in the UK. By the time this issue reaches you, Guy Fawkes Night ('Bonfire Night' in the UK) itself will have passed. But less well known is an attempt, 11 months earlier, to blow up the British Parliament with a tunnelled cache of explosives, rather than the less exciting option of a cellar rented beneath the seat of government itself.

The famous Guy Fawkes himself had earlier adopted the pseudonym 'Guido' Fawkes to join Catholic Spanish forces fighting the Dutch Republic. The sketchy history suggests that it was here he learned some rudimentary military tunnelling skills, which he would later try to use against the Protestant English ruling classes.

Unfortunately for the plotters, their limited skills were no match for the stone foundations. Or perhaps the alignment was off. It might be both, or neither; a lot of the information was obtained after several rounds of torture. The tunnel was never found. What is known is that the hapless traitors changed to the aforementioned cellar tactic, were discovered, and were hanged, drawn, and quartered.

Bonfire Night was celebrated for patriotic and religious reasons over the next few centuries. Many an effigy (a 'Guy') was burned. In the days following the recent financial crash, and a growing recognition of the excesses of the political and financial sectors, there has been a burgeoning, sometimes hysterical, backlash against the establishment. At least for the last decade, many people have been remembering the Fifth of November in an entirely different light.

I have spent some time recently reading blogs and opinions on the UK's newest planned rail link, High Speed Three (HS3). It doesn't read well for construction. Interspersed among

Alex Conacher  
Deputy Editor



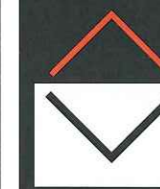
the disapproving NIMBY masses, the major advocates of the line are our unavoidably blue-blooded current political leaders. Prime Minister David Cameron, descended from King William IV; Chancellor George Osborne, who has somehow traced his lineage back to King Henry III; and less significantly for HS3 Mayor of London Boris Johnson, descended from King George II.

There was a Harding Lecture in London a few years ago delivered by Bill Grose. In it, he stressed the importance of engineers taking it upon themselves to advocate ambitious, sometimes controversial projects. To educate people, and articulate to them what can be achieved, and what improvements to their lives can be made.

If the engineering community wants HS3, or any project anywhere in the world, it should never just leave the job of promoting the scheme to the least popular people in society. And more importantly still, as Guido learned, a tunnelled solution is great at keeping the surface world blissfully unaware of progress. I see no reason why the Gunpowder Treason should ever be forgot

editor@tunnelsonline.info

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



### This month...

#### 20 YEARS AGO

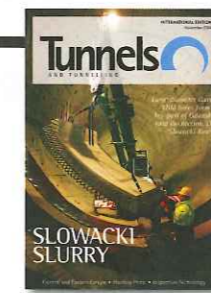
Work was abruptly halted on the night of 21 October as all three tunnels comprising the Central Terminal Area station complex on the new GBP 300M Heathrow Express link in London, UK began to collapse, calling into question the use of NATM in London Clay. The 1992, 100m trial tunnel appeared to confirm that London Clay was a suitable medium for NATM. Nevertheless, during the early hours, cracking appeared in the upline platform tunnel shotcrete lining. Progressive collapse occurred in all three tunnels. An investigation is to be conducted, it will take months to decide. *Tunnels and Tunnelling, November 1994, p.9*

#### 30 YEARS AGO

An ambitious scheme to build an underground missile base to withstand a protracted nuclear war, should one occur, is being studied by the US Pentagon. Likely to be located somewhere in the desert of one of the country's western states, the installation would consist of up to 650km of tunnelling over 1,000m below the surface. The idea is that base personnel would tunnel to the surface to launch retaliatory missiles within two or three days of the initial attack. These exit tunnels would have been all but holed through during initial excavation of the base, and passages would then be cleared through the rubble of a first strike. Tunnelling experts have stated that the project would take about five years to excavate and would cost an estimated USD 50bn. *Tunnels and Tunnelling, November 1984, p.11*

#### Cover

The front cover this month shows lining installation on the Martwa Wisla Tunnel in Gdansk, Poland



#### Next issue

In the next issue, Tunnels and Tunnelling looks again at Australasia, this time with a particular focus on New Zealand, which often gets ignored in favour of its larger neighbour. Also, we will carry a special bound-in supplement focusing on the latest in hydropower tunnelling

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## NEW EPBM FOR ISTANBUL METRO

Turkish contractors Gülermak, Kolin and Kalyon in Joint Venture have selected TERRATEC to design and manufacture the new EPB Tunnel Boring Machine for the construction of the rapid transit line in Istanbul between Mecidiyekoy and Mahmutbey.

TERRATEC takes pride in this achievement by expanding its sales coverage to Middle East and Europe. The Company currently has a subsidiary in Dubai covering the sales and after sales activities in the region.

TUNNELLING SOLUTIONS | METRO



Left: The Martwa Wisla road tunnel in Gdansk, p.24

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A professor, photographer, and urban explorer explores ghost stations beneath London

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To combat ageing infrastructure, innovative inspection techniques are needed to minimise disruption to everyday tunnel functions

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Angelos Gakis, Dr. Sauer  
This paper looks at the design of an SCL wraparound tunnel at Crossrail's Farringdon Station project

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GRANDS PROJETS

# HIGH SPEED THREE GOES AHEAD

**GREAT BRITAIN** — The Prime Minister and Chancellor for the Exchequer approved the UK's High Speed Three (HS3) rail project last month. The route will run east to west across the north of England, connecting the cities of Leeds and Manchester.

The ministers were responding to a report by David Higgins, who was asked by the Chancellor how to address poor east-west links in the north, and how to maximise the benefits of HS2. Higgins' also endorsed the two proposed routes for Phase Two of HS2, joining the London-Birmingham route with spur routes to Manchester and Leeds.

The government, working with Transport for the North (a new, unified transport body for the country's north), will now produce a comprehensive transport strategy for the region. This will include options, costs and a delivery timetable for a HS3 east west rail connection. An interim report will be produced in March 2015.

Transport Secretary Patrick McLoughlin said: "Our northern cities are on the brink of an economic transformation and [the] report underlines how we can secure this by bringing those cities together to maximise the benefits of good transport links."

The PM said boosting connectivity and reducing journey times was crucial to government's plan for the North.



### Right-wing think tank slams HS3 decision

**GREAT BRITAIN** — The Institute of Economic Affairs (IEA) has called the government and David Higgins "wholly misguided" over the backing of the High Speed Three (HS3) rail link between Leeds and Manchester.

Reacting to the decision to go ahead with the line, head of transport at the IAE Richard Wellings said, "The proposal for a new high-speed rail link in the north is little more than a costly vanity project. HS3 is an expensive and inefficient way to link northern cities, which are relatively close in distance. A high-speed rail line would make little difference to door-to-door journey times for most travellers, northern conurbations being geographically spread out to include numerous different towns.

"Rather than creating headline-grabbing policies, government resources would be better spent on smaller-

scale schemes that deliver high returns for the taxpayer, or, that can be financed by the private sector."

The Government feels the opposite, and plans to make Chancellor George Osborne's aims for a "Northern Powerhouse" the centerpiece of the budgetary Autumn Statement. A key part of this vision for the North will be interconnectivity of Northern cities, with the aim to improve the economic prospects of the north of the country and "rebalance" an economy seen by many as over-reliant on London. Osborne concludes, "The cities of the North are individually strong, but collectively not strong enough."

### Eisack River Tunnel contract awarded

**ITALY** — The Eisack River undercrossing project has been awarded. A joint venture comprising Strabag, Salini Impregilo, Consorzio Cooperative Costruzioni and Colli Lavori will excavate the twin tube, 4.3km tunnel.

The EUR 300M project will form part of the two main tubes of the future Brenner Base Tunnel. Other work involves two connecting tunnels to the existing Brenner Railway, adaptations and improvements to existing infrastructure, as well as environmental restoration after construction works.

The site is located at the southern end of the Brenner Base Tunnel near the town of Franzensfeste in Italy. While the surrounding mountains are granite, geology in the valley is thought to consist of stones in sand.

Thomas Birtel, CEO of Strabag said, "This is an extremely demanding project from a technical point of view, as it undercrosses the river Eisack, the Brenner Motorway, the state highway and the Brenner Railway with a very low rock overburden."

Work should begin before the end of the year and will last eight years in total.

Brenner Base Tunnel SE said it was unable to give much more detail on the project, due to ongoing value engineering discussions.

### SR99 repair pit construction begins

**USA** — Contractor Seattle Tunnel Partners (STP) has begun digging the circular pit crews will use to access and repair Bertha, the 17.5m-diameter SR 99 tunnelling machine.

On 17 October, an excavator rolled into position to the west of the Alaskan Way Viaduct near Pier 48, where STP stopped tunnelling last December after Bertha overheated. There, crews began taking the first scoops of soil from what will become a 36m-deep, 24m-wide pile-supported pit.

Because a number of "important construction activities" are competing for space near the pit, there will be many days when excavation doesn't occur.

Meanwhile, crews are continuing to lower groundwater in enclosed areas near the machine and prepare for installation of the massive crane that will be used to hoist pieces of the machine to the surface for repair later this autumn.

**Crossrail unworried by crane operator strikes despite union warnings**

**GREAT BRITAIN** — Crossrail does not expect operator strikes against crane hire company HTC will cause any delays to construction, due to limited presence by that company on Crossrail sites. Construction union UCATT had earlier announced that "sites set to be affected by the industrial action include: Crossrail, the London Bridge redevelopment, Nova Square Victoria, Elephant and Castle redevelopment and the Atomic Weapons Establishment at Aldermarston."

Specifically in response to Crossrail's statement, a UCATT spokesman added, "The action will have a major affect at Farringdon as well as on other parts of the Crossrail project."

Contractors affected by the action are alleged to include: Kier, Lend Lease, Bam, Costain, Mace and Vinci.

The industrial action was announced after UCATT



HTC cranes operating in London (not a Crossrail site)

balloted 180 crane operators during an argument over pay. The 180 plus crane drivers had a vote of 94 per cent in favour of strike action and 94.6 per cent in favour of industrial action short of strike action.

The turnout was in excess of 80 per cent.

According to Cranes Today magazine, HTC has offered its operators a three per cent pay rise, with another three

per cent coming next year. HTC managing director Dave Holder says, "Our offer of three per cent [...] double the rate of inflation. We see this as a fair and just reward. It's coupled to another three per cent offer next year as well, so it's six per cent over two years in all."

UCATT counters that the offer doesn't restore operators' wages to pre-2009 levels.

Secretary general Steve Murphy says, "Crane drivers are fed up. They have endured years of pay cuts and seen their pay fall in real terms."

The industry is booming but their employers are not prepared to pay up."

Holder disputed the union's claim, saying, "It is simply untrue to suggest pay levels are below 2008 figures."

"Any operator who joined HTC after 2011 has enjoyed year on year, above inflation pay increases."

"Whilst our utilisation is currently very healthy, our revenues are some considerable way from where we would like them to be."

**NCC to build E134**

**NORWAY** — NCC has won a SEK 1.14bn (USD 158.3m) contract to build a new tunnel along the E134 highway between Gvammen and Århus in Telemark, Norway.

The 9.4km long tunnel will direct traffic in two directions from Gvammen to Århus which will help reduce the length of the E134 highway by nearly 11 kilometres.

Improvements will also be made to accessibility and road safety along the new section of highway.

The scope of the contract includes construction of 1.1km of roads on either side of the mountain, 5km of local roads and two crossings, multiple smaller bridges and portals, and other structures along the section.

The proprietary "Green Construction" concept of the company will be applied on the sites of the current project.

The project is expected to begin this year and will be completed by 2019.

**CROSSRAIL TWO PREFERRED ROUTE IS OUTLINED**

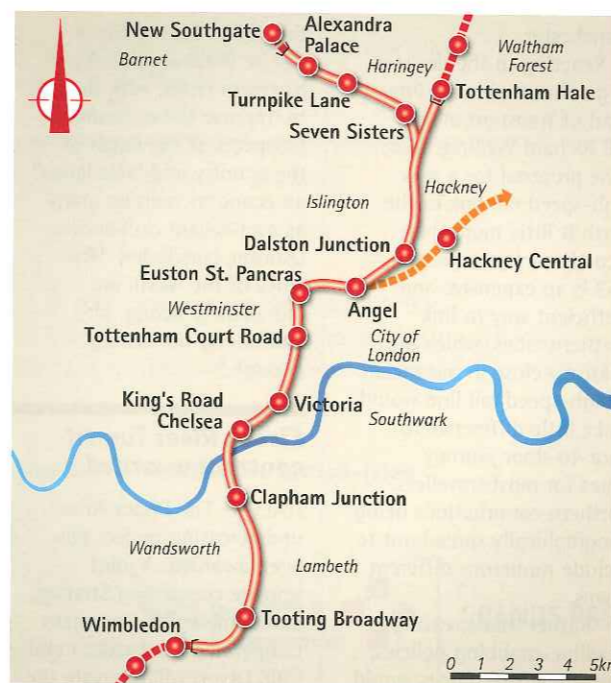
**GREAT BRITAIN** — Mayor of London Boris Johnson has outlined a preferred route for Crossrail Two. The GBP 20bn (USD 32bn) scheme will run north-south through London. This second route is vital to the UK capital's growth, according to Johnson, who expressed confidence that the private sector could contribute over half of the cost "in the right circumstances".

If approved by the government, construction could begin as early as 2017, with the route operational by 2030. The original Crossrail project is scheduled to begin to enter operation

in 2018.

Although 2015 will see much weighing of options, the basic plan is for a tunnel from Tottenham Hale in the north to Wimbledon in the south, a 36km-long drive at a depth of 30m.

In a recent consultation, support for Crossrail Two is high. Some 83 per cent of respondents 'strongly supported', or just 'supported' Crossrail 2. And 78 per cent of stakeholders answered the question regarding support for the scheme, and from those 95 per cent 'support' or 'strongly support' the project.



**KVMRT PROJECT**

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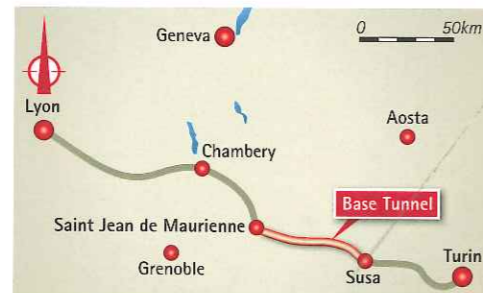
## FUNDING SECURED FOR LYON-TURIN TEST BORE

**FRANCE/ITALY** — Funding for the latest test bore on the Lyon-Turin base tunnel project has been approved. The 9km drive from Saint-Martin-de-la-Porte in southeast France will eventually form part of one of the main 10.5m-diameter, 57km-long twin tunnels that will connect Italy and France.

Following the signing of the EUR 105.78M (USD 133.83M) deal on 1 October, tenders can now be issued and construction should begin in January 2015.

An adit in the vicinity was constructed through Carboniferous Formation, a highly heterogeneous, overstressed and in cases anisotropic rock mass exhibiting a squeezing behaviour.

The first phase of the Lyon-Turin base tunnel project was budgeted to cost approximately EUR 8.5bn (USD 10.78bn). At signing, the EU was



expected to fund 40 per cent of the project cost, with Italy to contribute 57.9 per cent of the remaining, and to provide 42.1 per cent of the remaining.

The standard gauge (1,435mm) track will have operational speeds of 250kph and will carry both passenger and freight traffic when the route is complete.

### Klang Valley Mass Rapid Transit Line Two could begin next year

**MALAYSIA** — Work on the Klang Valley Mass Rapid Transit line Two (KVMRT 2) project, a 56km line from Selayang via Kuala Lumpur to Putrajaya, could start next year following an announcement by Malaysian prime minister Datuk Seri Najib Tun Razak during the 2015 budget unveiling on 10 October 2014.

The project is expected to cost MYR 23bn (USD 7.08bn) and take five years to complete, inclusive of preparation work, land acquisition and moving utilities.

However, Razak's announcement that the line would run to Selayang rather than Sungai Buloh as initially thought has caused some to question whether an additional depot is required. A 65 hectare depot for Line One is currently under construction adjacent to Rubber Research Institute station which was expected to have sufficient capacity for Line One's fleet of approximately 50 trains and

the 50 required trains for Line Two.

The Land Public Transport Commission (SPAD) was reported in July to have completed a pre-feasibility study for the Selayang to Putrajaya alignment which was said to be under review by the Ministry of Finance.

The first MRT line, a 51km line from Sungai Buloh to Kajang, construction of which got underway in 2011, is now 50 per cent complete with most of the civil works on course to finish next year. The line is due to open in 2017. Upon completion, it will have 31 stations serving 1.2 million commuters with links to existing public transport systems.

The whole MRT project is proposed to include three lines where the last one is a circle alignment running around the Kuala Lumpur City Centre.

### Melamchi Drinking Water Project is one third complete

**NEPAL** — Melamchi Water Supply Development Board (MWSDB) said that 31.77 per cent of tunnel construction

work of the Melamchi Drinking Water Project has been completed by 7 October 2014. This means a total of 8.76km of tunnel, out of the total length of 27,582-metre diversion tunnel, has been constructed.

According to MWSDB, Italian contractor — CMC Cooperativa Muratori e Cementisti — constructed 201m section of the tunnel in the last three weeks. Going by the agreement, the contractor has to complete the tunnel works by September 2016.

On 30 September 2014, a team of government officials led by Secretary at the Office of the Prime Minister and Council of Ministers Shanta Raj Subedi had inspected the tunnel works and water treatment plant at Sundarjal.

The Prime Minister's Office had said that the inspection team found that 34 per cent work of the water treatment plant had been completed. During the visit, Subedi had directed the contractor to carry out construction work of the tunnel and treatment plant round the clock so that the project could be completed before the deadline.

This year, the government has allocated NPR 4.61bn (USD 46M) budget to the project, which was started 14 years ago with a target to bring 170 million litres of water per day to Kathmandu Valley. The government aims to bring Melamchi water to Kathmandu by April 2016.

The Italian contractor was appointed last year after the government terminated the contract with the Chinese venture — China Railway 15 Bureau Group Corporation and China Machinery Industry Construction Group Inc — in September, 2012. The Chinese contractor had constructed only 6,500m of the tunnel over three years.

### MRT line to receive Asian Development Bank assistance

**INDONESIA** — The Asian Development Bank (ADB) has offered to extend technical assistance to the Jakarta city administration to support the mass rapid transit (MRT) project's east-west route.

The route ranges from Balaraja in Banten to Cikarang in Bekasi, West Java. The administration is still conducting a feasibility study for its construction. MRT president director Dono Boestami said the city is still discussing the ADB's offer.

"The ADB offered technical assistance for the east-west MRT route. The assistance includes financial provisions for transaction advisory services to ensure that world-class financial and legal advisers are appointed to the project," Dono said in Jakarta on 8 Oct. 2014.

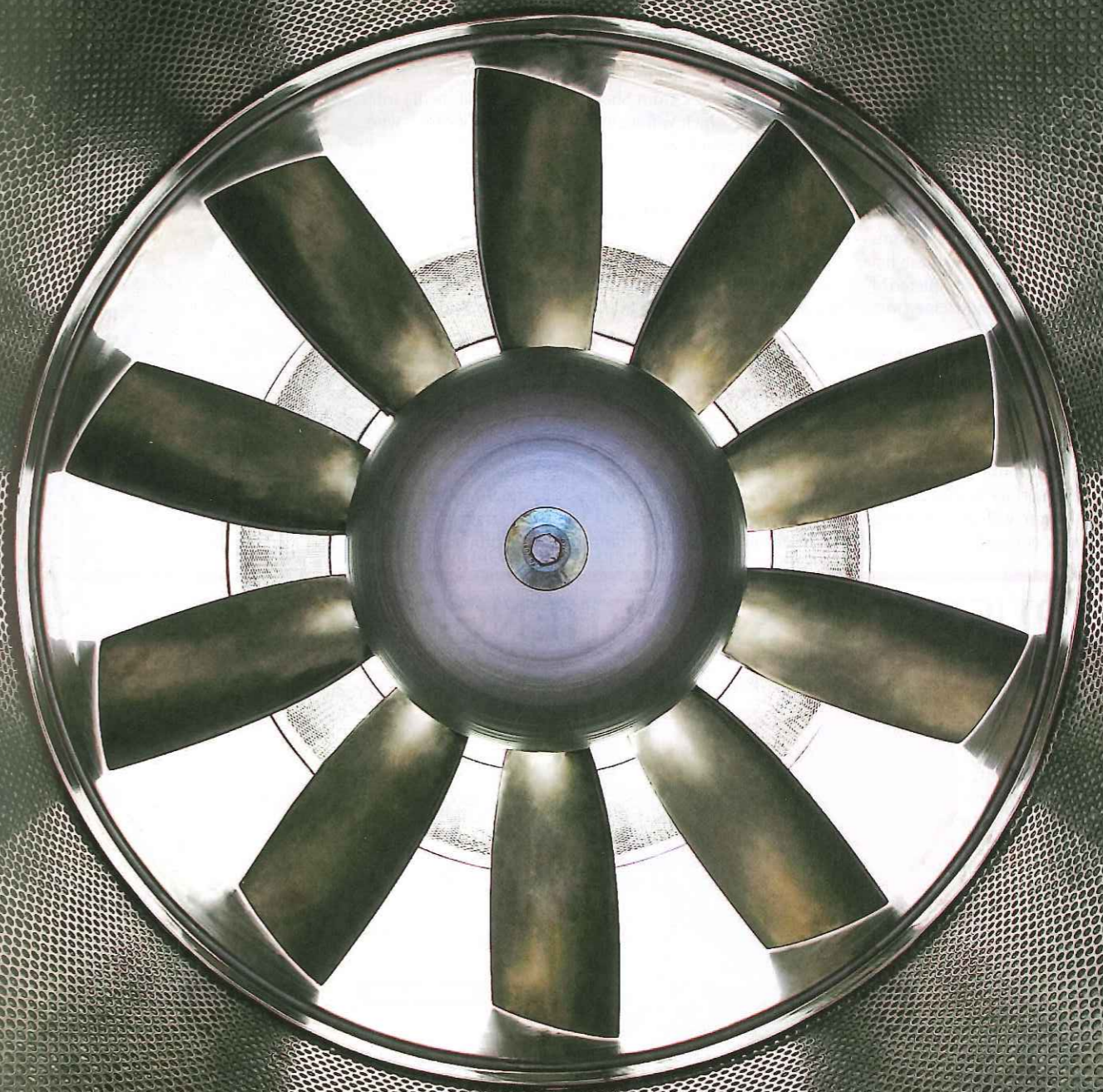
However, he said the city administration is focusing on the north-south MRT route and the construction of the planned six toll roads.

"Pak Ahok wants to focus on the six toll roads so he is still considering the ADB's offer," Dono said, referring to the capital's incoming governor Basuki "Ahok" Tjahaja Purnama.



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**First Shiraz line inaugurated**

**IRAN** — The first phase of Shiraz Urban Railway Organisation's metro Line One was officially opened by Vice-President Es'haq Jahangiri on 11 October. The initial section runs for 10.5km between Ehsan Square in the north of the city and Namazi in the centre, with eight stations-- although two of these have not yet been completed. Construction of Line One began in 2001. In the second phase, the line is to be extended south from Namazi to Gol-e-Sorkh Square near the airport, taking it to 22.5km with 20 underground stations and one surface station. Much of the line will be underground, with cut-and-cover sections

and 12.5km of twin 6m diameter tunnels bored by a pair of earth pressure balance TBMs supplied by NFM Technologies. Construction is also underway on the initial 11km phase of Line 2 from Shokufe to Azadi, which will include an interchange with Line 1 at Imam Hossein Square. A second phase is planned, which will extend the line 4km east to Saadi.

A 10km Line Three with five stations is planned, along with Lines Four, Five and Six.

**New York City train struck by drill bit**

**USA** — A construction drill broke into a tunnel under New York and hit the side of a train early this month. According to the city's Metropolitan Transportation

Authority (MTA) the accident was caused by human error, rather than faulty equipment. The drill operator broke through approximately 7ft (2m) away from his intended position.

Local media interviewed workers nearby, who described the sound of the 10in (254mm) drill hitting the train as a "loud boom", and "like when you're drilling and you hit a stone". Reportedly workmen began running around, and a "textbook" train evacuation was carried out.

The workman was reportedly employed on the East Side Access project, and was fully qualified. An MTA spokesman added that officials on the site near 23rd Street and 41st Avenue have determined further drilling on the project is not needed.

**Temporary station at Abbey Wood**

**GREAT BRITAIN** — A temporary station at Abbey Wood has opened to allow work for the new Crossrail station to get underway.

The temporary station includes a staffed gate line, ticket machines and windows, a cash point and, for the first time, lifts to all platforms. Work will shortly get underway to remove the existing station building.

The new station will open in 2017 and will be built above two new dedicated Crossrail tracks.

The work at Abbey Wood is being carried out by Network Rail, which is responsible for the design, development and delivery of the parts of Crossrail that are on the existing rail network.

**PUSH FOR STONEHENGE TUNNEL**

**GREAT BRITAIN** — The UK Government has set up a working group to reconsider shelved plans to construct a tunnel under Britain's famous Neolithic monument, Stonehenge. The World Heritage Site also plays host to the heavily congested A303 highway. A tunnel would enable it to be dualled, reducing congestion and protect the area.

A decision is expected in the Chancellor for the Exchequer's Autumn Statement on 3 December, after MP for Salisbury John Glen hailed a tunnel as the "only realistic solution", arguing that a long deep bore tunnel would enable safe passage through without disturbing the hidden barrows and earthworks of the site.

A push for a tunnel was defeated in 1996, and again in 2007 due to cost overruns. The second attempt also saw the National Trust state its preference for a 4km deep tunnel over the original 2km cut and cover vision. In July 2005, Roads Minister Stephen Ladyman announced a review of the options following a cost rise from GBP 284M (USD 505M) when the draft orders were published in 2003 to some GBP 470M (USD 836M). The increase was attributed to very large quantities of weak phosphatic chalk, and a high



water table.

The Highways Agency claimed groundwater levels could rise to the surface at times of heavy rainfall where the proposed tunnel alignment passes below a shallow valley to the south of Stonehenge. These factors were felt to complicate the tunnelling process and extend the overall construction programme.

In a statement, the National Trust said, "We would like to see the longest possible tunnel but we recognise that any plan needs to be both affordable and deliverable."

A Department for Transport

spokesman said: "We are discussing a range of potential options for improving the A303/A30/A358 corridor with interested parties to understand their views, including consideration of the section of the A303 that passes Stonehenge. No investment decisions have been made as this is work in progress."

According to the office of John Glen, a dualled A303 through a tunnel should generate "over GBP 41bn (USD 65.73bn) for our economy, create 21,400 jobs and increase tourism expenditure by GBP 8.6bn (USD 13.79) every year."



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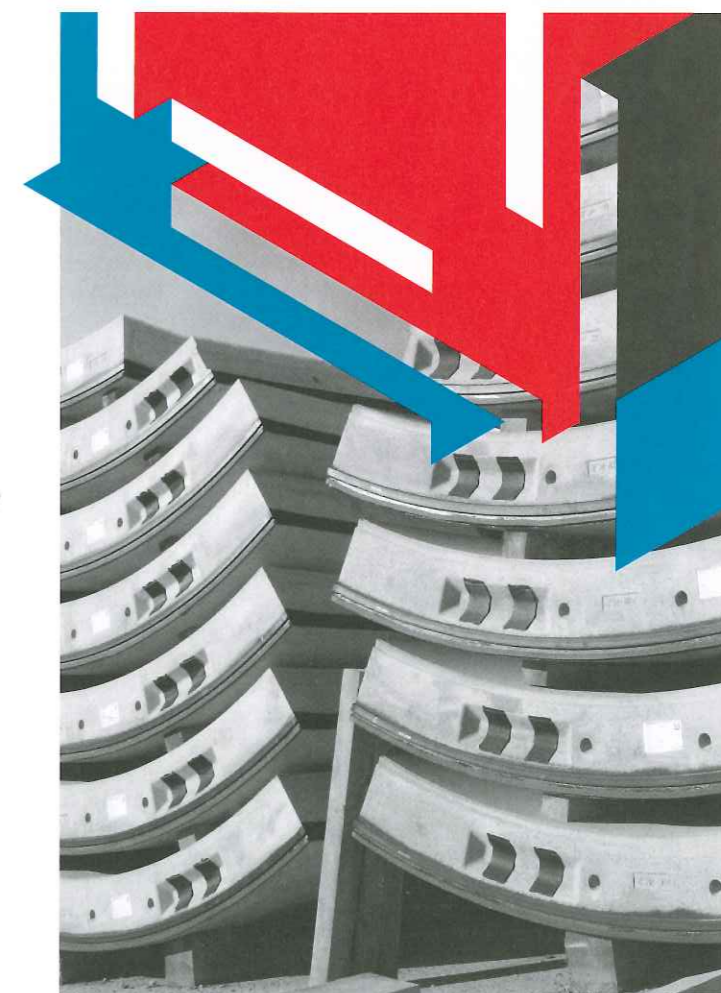
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## AECOM AWARDED MAJOR HONG KONG SEWAGE CAVERN

**HONG KONG** — Aecom has been awarded a USD 130M contract to design Asia's largest ever cavern-based sewage treatment works. The cavern will accommodate the relocated Sha Tin Sewage Treatment Works (STSTW).

The Drainage Services Department of Hong Kong's Special Administrative Regional government awarded the contract.

The finished project will have a sewage treatment capacity of 340,000cu.m per day, serving a population of 800,000 in the Sha Tin area.

An Aecom spokesman said, "Aecom's scope of works includes engineering and environmental impact assessments, design of sewage treatment process, all aspects of engineering and architectural design in relation to the sewage treatment works in caverns, preparation of tender documents and construction supervision.

"Aecom will also assist the government in public engagement activities and provide

preliminary design for the upstream sewerage networks and pumping facilities related to the relocation of the STSTW to caverns.

"To design a sustainable sewage treatment works located inside caverns that will meet the demands for the next several decades, Aecom's cavern and process teams will work out advanced sewage- and sludge-treatment technologies to minimise the size of needed caverns, energy consumption, carbon footprint and sludge production, in order to optimize the cost of the entire life cycle."

"Aecom will organise pilot studies to ensure that state-of-the-art technologies work well for local sewage characteristics, including high salinity due to the use of seawater for flushing in Hong Kong."

The investigation and design work are scheduled for completion in phases from 2017, and construction works will commence afterwards.

management in the emirate, said on 12 October.

The pumping stations themselves will be completed by the end of 2015, he said.

After completion, the project will be commissioned in phases, Thomson said. The entire project is expected to be operational by 2016, he said.

The eco-friendly tunnel will drastically reduce the carbon footprint of Abu Dhabi's sewerage system and save SAR 4.2bn (USD 1.12bn) which can be spent on energy and maintenance costs in the next 25 years.

The project is part of the Strategic Tunnel Enhancement Programme (STEP) which costs SAR 5.7bn (USD 1.52bn). The deep tunnel – starting at 27 metres underground and reaching a depth of 100m – will not require regular maintenance for the next 80 years.

The project began in 2009. The tunnel starting from Karama area in Abu Dhabi city to Al Wathba treatment plant will triple the capacity of Abu Dhabi's sewerage network. The existing system deals with 400,000 cubic metres of sewage a day, but the new tunnel can carry 1.7 million cubic metres of sewage, which is the expected demand by 2030.

The new tunnel will do away with 34 pumping stations in the existing system that consume huge amounts of energy.

They will be replaced by one pumping station at Al Wathba treatment plant, he said.

### London road upgrade plan released

**GREAT BRITAIN** — Transport for London (TfL) has released its "Road Modernisation Plan". This GBP 4bn (USD 6.36bn) investment includes maintenance and improvement of several existing tunnels. More information on TfL's website.

### MRT tunnels below Bukit Bintang completed

**MALAYSIA** — The construction of the twin MRT tunnels beneath Jalan Bukit Bintang in Kuala Lumpur has been completed with the breakthrough of two tunnel boring machines into a reception shaft. This was reported by "Bernama", the National News Agency of Malaysia.

Mass Rapid Transit Corporation Sdn Bhd director of strategic communication and public relations Amir Mahmood Razak said one of the TBMs broke through on 16 October while the other emerged on 21 October.

"The overall progress of the MRT project underground works stood at 68.5 per cent as at the end of September, while the overall tunnelling completion is 88 per cent.

"We have just two TBMs digging up from the Pudu Shaft leading to Pasar Seni. All tunnelling works are expected to be completed by the first quarter of 2015, but underground works will

continue until December 2016," he told reporters at the MRT Pudu Launch Shaft site on 27 October.

MMC-Gamuda Head of Tunnelling Ng Hau Wei said the completion of tunnelling was very challenging due to the geology of the area.

"Jalan Bukit Bintang straddles two geological formation - the eastern end of Jalan Bukit Bintang sits above the Kuala Lumpur Limestone Formation while the western end is above the Kenny Hill Formation, the transition between these two formations is at the Pavilion area," he said.

Another challenge was the high concentration of utilities, he said, adding that, however, the use of high precision engineering technology, including Variable Density TBM had mitigated the problem.

"Besides significantly reducing the incidence of sinkhole formation, it is able to convert from the slurry shield mode (when tunnelling through limestone formations) to earth pressure balance mode (when

tunnelling through Kenny Hill formations) and vice versa," he said.

The Sungai Buloh-Kajang MRT, which will cover 51km in total, will run through the city centre, with 9.5km underground.

There will be seven underground stations, namely KL Sentral, Pasar Seni, Merdeka, Bukit Bintang Sentral, Pasar Rakyat, Cochrane and Maluri.

### Abu Dhabi green sewerage tunnel to finish early next year

**UAE** — Construction work on a 41km long 'green' tunnel in Abu Dhabi, one of the largest and longest gravity-driven sewerage networks in the world, is on schedule, a senior official said.

The 41km long main tunnel and 42km long link service tunnels will be completed by the first quarter of 2015, Alan Thomson, managing director of Abu Dhabi Sewerage Services Company (ADSSC), an Abu Dhabi Government entity responsible for waste water

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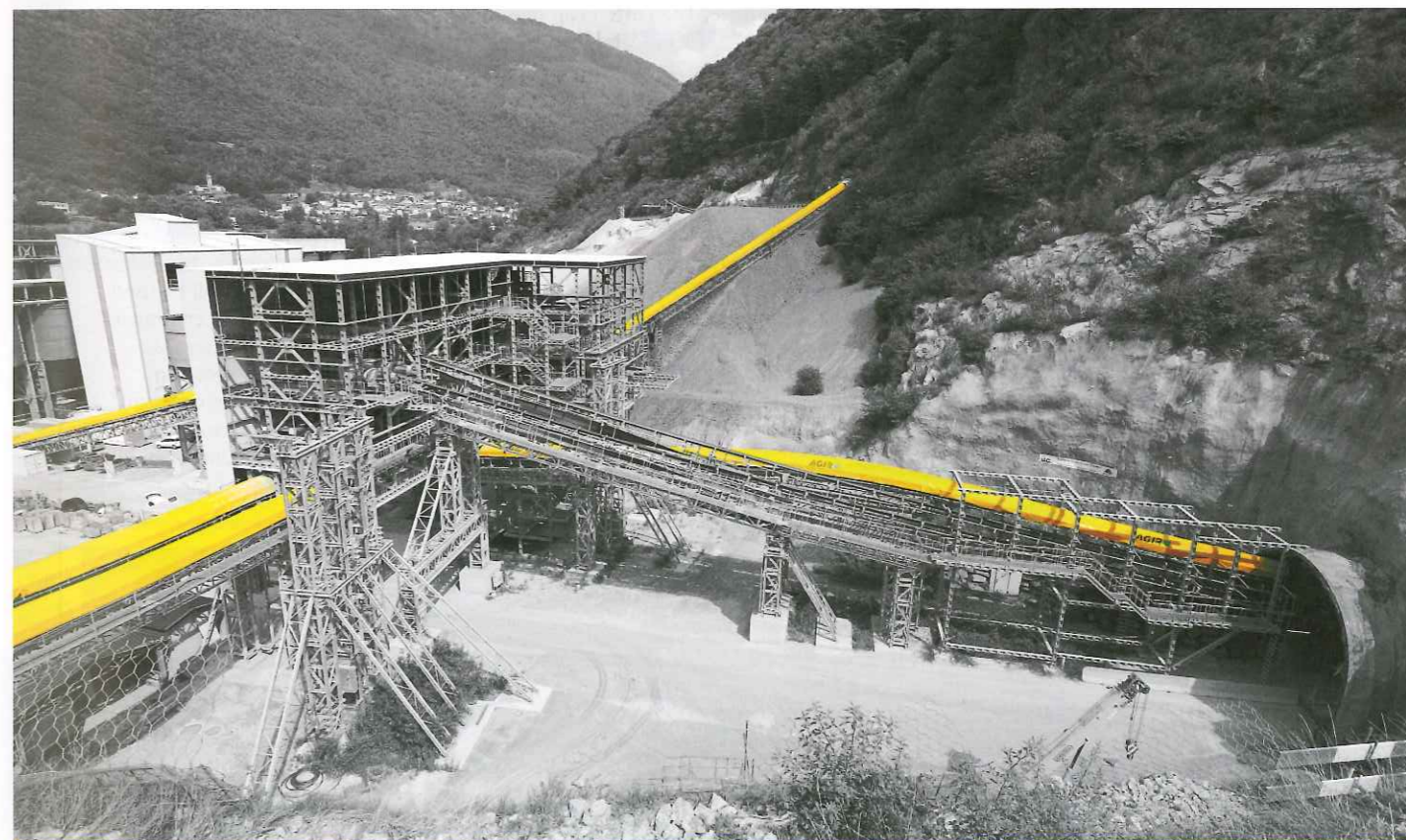
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**Silvertown Tunnel out to public consultation**

**GREAT BRITAIN** — The Silvertown Tunnel has been put out for public consultation. Local residents are being asked for their views on the proposed tunnel under the Thames in East London. The undercrossing would connect Greenwich Peninsula with the Royal Docks.

expects the project will cost approximately GBP 750M (USD 1.2bn).

The public consultation on the Silvertown Tunnel will run from 15 October until 19 December 2014. Further information about the consultation and the questionnaire can be found at [www.tfl.gov.uk/silvertown-tunnel](http://www.tfl.gov.uk/silvertown-tunnel). A report on the findings of the Silvertown Tunnel consultation will be presented to Boris

Johnson, the Mayor of London, in spring 2015 and made publicly available on the consultation website. A further consultation is planned for early summer 2015 ahead of the submission of an application for a Development Consent Order by the end of 2015.

Johnson said, "The Silvertown Tunnel would provide a vital new link beneath the Thames from two of our city's great opportunity areas for new homes and jobs - Greenwich Peninsula and the Royal Docks. It has quite rightly been classified by the Government as a project of national significance and today we're a step closer in making our vision a reality. "Unless new river crossings are provided, the huge growth potential of east London will not be realised, which is why I have asked Tfl to also take forward further work on two new river crossings to the east of the Silvertown tunnel at Gallions Reach and Belvedere. These new crossings will be essential not just for east London, but for the capital as a whole and its continued success as the motor of the UK economy."

Michèle Dix, Tfl's managing director of planning, said, "The recent public consultations have been very important, helping us to identify the best solution for new river crossings. It is clear that public support for more river crossings is high. These detailed plans for the Silvertown Tunnel are the next step in delivering a series of crossings that will keep London moving. The consultation is an opportunity to find out more about the design of the tunnel, how it will be used and the benefits and impacts of this new crossing."

Subject to securing funding and the necessary approvals, the crossings could be completed and open by 2025.

**MULTIPLE DELHI BREAK-THROUGHS FOR TERRATEC**

**INDIA** — TBM manufacturer Terratec has announced four new breakthroughs on its Delhi Metro worksites. The contracts concerned are CC-24 and CC-34 for the metro's third phase. The breakthrough details were as follows:

- On 8 September TBM S37 on contract CC-34 completed excavation on the down line from the Vikas Puri Station to the cut and cover shaft near to the Janakapuri West Station. The contractor is joint venture between Hindustan Construction Company Ltd. of India and Samsung E&C of Korea.
- On 30 September TBM S28 on contract CC-24 breakthrough after completing the drive between the Nizamuddin and Ashram Stations. The contractor was a joint venture between J.Kumar Infraprojects of India and China Railway Third Group (CRTG) of China.
- On 7 October TBM S36 on contract CC-34 completed excavation on the up line to the cut and cover shaft near to the Janakapuri West Station, like its twin S37 one month earlier.
- On 19 October TBM S26 on contract CC-24 completed excavation on the down line from

the Lajpat Nagar Station to the Vinoba Puri Station.

A Terratec spokesman discussed the machines' technical specifications. "Terratec's S36 and S37 TBMs are 6.52m-diameter EPB Shields with a classic soil configuration equipped with a Spoke-Type cutterhead of 58 per cent opening ratio, which has been proven to be very efficient to excavate this type of soil along the drive. The cutterhead mounted soft ground tools, but it is designed to allow the replacement for 17in roller disc cutters, making the TBM to be able to bore through the diaphragm walls and cope with the presence of any unexpected obstacle on its way, such as old wells or foundations.

"The S26 and S28 TBMs are 6.61m-diameter mixed/rock EPBMs. The TBMs mount 960kW VFD electric driven cutterhead with a versatile design, which mounts 17in roller disc cutters interchangeable for soft ground cutting tools."

The spokesman added that the mixed/rock EPB design had already been successful boring quartz rock with uniaxial compressive strength over 200MPa on earlier Delhi work.



The manufacturer has won a large share of Delhi Metro work

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



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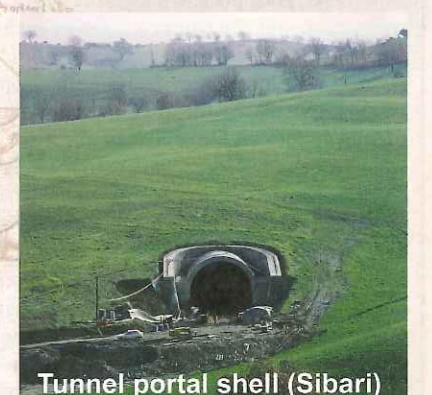
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Nazzano tunnel (Italy)

## JACOBS ASSOCIATES AND MCMILLEN TO MERGE

**USA** — Jacobs Associates and engineering and construction company McMillen have announced their intention to merge. In a joint statement last month, a spokesman for the companies said the competencies of each would benefit the other. First discussed in January 2014, the merger will come into effect on 1 December 2014. At this time the structure of the newly formed McMillen Jacobs Associates will also be confirmed. The companies have confirmed that the new entity will be a California corporation, and will operate with decentralised management.

"Jacobs Associates has focused primarily on detailed design and construction engineering in the heavy civil underground market since it started doing business in 1954. Merging with McMillen helps Jacobs Associates achieve three of its strategic initiatives: growing construction management, redefining how design-build is delivered, and diversifying beyond tunnels.

"McMillen LLC, which was founded in 2004, is an environmental, engineering, and heavy

civil self-performing construction firm with close ties to the hydroelectric infrastructure and water resources industries. Merging with Jacobs Associates will expand McMillen's geographical reach as well as strengthen its engineering capabilities in rock mechanics, grouting, and underground structures."

McMillen Jacobs Associates, will have a staff of 380, working out of 19 offices across North America, Australia, and New Zealand. Some 150 of these staff come from McMillen and 230 from Jacobs Associates.

McMillen places a particular emphasis on being "woman-owned". On the new structure, a spokesman said: "Preserving the corporate identity of McMillen is important.

"McMillen and Jacobs Associates have common interests in the role women play in ownership and management of our firms. Both companies currently have women ownership with executive leadership roles held by women. McMillen Jacobs Associates will continue in this manner in the future."

### LNSS buys Caterpillar's dropped tunnelling business

**CANADA** — Liaoning Censence Industry (LNSS) has acquired the fixed assets and entire Intellectual Property of Caterpillar Tunneling Canada Corporation (CTCC). The two companies entered into an Assets Purchase Agreement in January 2014, and a closing ceremony was held at CTCC's facilities in Toronto, Canada.

LNSS is a TBM manufacturer based in China. A spokesman claimed it possesses the biggest TBM manufacturing capacity in the country.

Following the acquisition, LNSS has set up its wholly-owned subsidiary Lovsuns Tunneling Canada Ltd ("Lovsuns") in Toronto.

The new entity will be responsible for operating the acquired assets and will "assume the strategic role of LNSS's overseas engineering, manufacturing and sales/service centres". Earlier this

year, Paul Clark, Caterpillar general manager with responsibility for tunnelling said, "For the past year, LNSS has been a CTCC manufacturing partner for the sale of TBMs in China."

"Through this partnership, CTCC and LNSS collaborated to produce three Caterpillar branded TBMs for use by customers in China. Given this relationship, this agreement was a natural next step for both sides."

### Aecom completes URS acquisition with confidence in the future

**USA** — Aecom announced on 17 October that it had completed the USD 6bn acquisition of URS Corporation. Stock issuance proposals were accepted at each company's respective stockholder meetings on 16 October.

"Today is an exciting and historic day - for our industry, for Aecom and URS, and for our nearly 100,000

people around the world who are serving our clients in over 150 countries," said Michael S. Burke, Aecom CEO.

"During the past three months, as we have advanced our integration planning efforts, my belief that Aecom and URS had highly complementary operations and cultures has been solidly confirmed," Burke said.

He then added: "Our leaders have collaborated to develop a comprehensive integration plan that will leverage our greater scale across our global platform. We are confident that we will achieve our target of USD 250M in annual cost synergies."

### Ferrovial results boost revenue increase

**SPAIN** — Ferrovial, a global infrastructure operator and manager of municipal services, obtained EUR 701M (USD 875M) in EBITDA in the first nine months of 2014. This was an 11 per cent increase, on a 10 per cent

growth in revenues which then amounted to EUR 6.5bn (USD 8.1bn). Results were boosted by a good business performance, particularly in the services and the international construction business areas.

### HCC posts sixth consecutive quarter of profits

**INDIA** — Contracting giant HCC has registered Operating Profit of INR 1.75bn (USD 28M) for the second quarter of FY 2014-15 compared to INR 894M (USD 14.6M) in the corresponding period last year.

The company gave its Financial highlights for the quarter ended 30 September as: turnover at INR 9.59bn (USD 156M) against INR 9.09bn (USD 148M) on year-on-year basis; operating profit at INR 1.75bn (USD 28M) compared to INR 894M (USD 14.9M) on year-on-year basis; EBITDA margins at 18.8 per cent compared to 10 per cent on year-on-year basis; Net Profit of INR 68M (USD 1.1M) compared to INR 316M (USD 5.1M) on YOY basis; current order book stands at INR 136.8bn (USD 2.2bn), excluding L1 contracts worth INR 23.7bn (USD 386M).

Commenting on the company's performance, Praveen Sood, Group chief financial officer said that "the performance of HCC should be viewed keeping in mind that extra ordinary flood affected operations at Jammu & Kashmir, where the company is executing major projects.

"However, sustained and focused efforts to improve its operational efficiency helped in maintaining the turnover growth in spite of this setback.

"The company is fully geared to take up new projects to be announced by the government. HCC will further aim at consolidating its financial parameters in the coming quarters."

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# DEMAND FOR PLACES SOARS AT WARWICK

The British Tunnelling Society-supported Tunnelling MSc is replete with students as bursaries flood from the wider industry

**W**ARWICK UNIVERSITY'S Tunnelling and Underground Space MSc has seen more than a 50 per cent increase in student numbers on last year. According to course director Benoit Jones, this substantial increase ensures the course's sustainability, and that it covers its own costs, as well as being promising for the industry.

Jones adds, "All 33 graduates are now working in the tunnelling industry, mainly in the UK, or are about to start (the 2013/14 year having only just finished). The graduates of the course seem to be much in demand and I often get asked by companies if there are any looking for employment. I always tell them the best way to employ a graduate of the MSc is to sponsor one."

From the start, the British Tunnelling Society (BTS) was instrumental in helping to set up the course. Its Education Committee acts as the steering board for the MSc, and so meets with Jones a couple of times a year to discuss the



Above: Warwick engineering student

## Course modules

Each credit represents about 10 hours of student work. About 2 hours out of 10 is contact time – lectures, labs, example classes. The rest is self-study. So the whole course is 180 credits = 1800 hours' work. Therefore it is full time for 12 months from October to September. Part-time students do the course over 24 months. For each 15 credit module, the teaching time is condensed into 1 week (Underground Construction Methods has two weeks of teaching). This makes it easier for part time students to come for a week for each module, then go back to work. It also means that most of the modules (except the Project and Professional Skills) are available for external candidates to do as a short course.

- Underground Construction Methods (30 credits)
- Geological Investigation and Ground Characterisation (15 credits)
- Professional Skills (15 credits)
- Rock Mechanics (15 credits)
- Tunnel Design (15 credits)
- Construction Management (15 credits)
- Health, Safety and Environmental Considerations (15 credits)
- Finite Element Methods for Tunnelling (15 credits)
- Project (45 credits)

curriculum and other matters.

Aside from this, industry involvement has been key. Across the whole course, approximately 20 per cent of lectures are given by a guest industry specialists. Each module has a 'champion' who provides advice on the syllabus for each module and help find guest lecturers for specialist topics or case studies. This ensures the course is well-grounded in current best practice. The BTS also provide a GBP 500 (USD 803) prize each year for the best student, and the Terry Crabb Memorial Trust provides a GBP 500 prize each year for the best project.

BTS chair Roger Bridge explains the organisation's motivation. "The aim is to encourage more engineers into the tunnelling industry and furnish those engineers with a grounding in the skills and knowledge of the processes specific to the tunnelling industry. From an early stage it was identified and agreed that representatives from industry were an excellent way to convey the most up to date thinking."

The number of applicants to the course is substantially higher than the number of students that end up subscribing. Bridge notes that, during the development of the course, student numbers in the mid-twenties were discussed as a target, and that bursaries and sponsorship are an important part of the project. "We are aware that a number of the applicants subsequently realise the financial implications. This is part of the reason that the BTS provide a bursary and we are pleased to see [a number of companies following suit]."

"Although the Government has acknowledged the importance of the industry and the need to ensure sufficient competent resources are available they remain firm in their policy not to provide funding for students undertaking MSc Courses which will restrict the ability of many individuals to attend."

Table 1. Tunnelling MSc student numbers growth

Year	Full-time students	Part-time students
2011/12	8	3
2012/13	11	4
2013/14	11	3
2014/15	16	7

Source: Benoit Jones of Warwick University, UK

According to Jones, the BTS provides a GBP 12,000 bursary to one student each year. Morgan Sindall provides five GBP 15,000 bursaries each year and Balfour Beatty provides one or two GBP 15,000 bursaries each year. The part time students receive varying degrees of support from their employers – some pay the fees and give the student time off to attend modules and exams, some make the student pay the fees but are flexible in allowing them time to attend modules and exams. The course currently has, and has had in the past, part time students from URS (4), CH2M Hill (2), Network Rail, DSJV, Donaldson Associates, Mott MacDonald and Morgan Sindall.

When asked about the possibility of students taking their acquired knowledge elsewhere, Bridge says, "I don't believe we can be selfish and feel we have lost out if engineers undertake the training and then choose to pursue careers abroad. At the moment a large number of the engineers from the UK that attend the course remain in the UK. The buoyancy of the industry and the pipeline of work has generated a demand for experienced and competent engineers and this was the reasoning behind the establishment of the course."

T&T spoke with Colin Eddie of Morgan Sindall, to discover the business case for sponsoring so many students. "Our motivation is very much business driven. The offer of GBP 15,000 in

sponsorship to study the MSc enables us to attract the very best candidates. These high calibre candidates then receive an excellent education on the MSc and go on to join business.

"Establishing the business case for such a specialist course was a tough challenge for the University and it is testament to the tenacity of [Warwick's] Tony Price that the course was established and now enjoying the International recognition it deserves.

"The BTS and Warwick University should be justifiably proud of their contribution in closing this skills gap."

As for the future, there is discussion at BTS meetings of possible evening courses, due to the concentration of young engineers in London. The BTS has said it would support this in principle, but the mechanics have not yet been explored

Below: University of Warwick campus

Alex Conacher



London Underground's abandoned Aldwych Station was finally closed in 1994. Photographer, academic and urban explorer Bradley Garret has recently published a photographic journey through the forgotten depths of the city.

SUBTERRANEAN LONDON:  
CRACKING THE CAPITAL  
BY BRADLEY GARRETT,  
PUBLISHED BY PRESTEL



# GDANSK DOUBLE

**T**HE CITY of Gdansk, Poland, is investing in major road improvements between its airport and port, and the key project to the success of this 10km long "Slowacki Route" is a relatively short twin tube tunnel below Martwa Wisla, the main shipping waterway out to the Baltic Sea.

The bored tunnels of the underground link are each only 1072m long, but to excavate steeply through the alluvial and glacial deposits of the coastal plain, and do so under a high water table, called for a major slurry TBM operation.

Spanish contractor OHL used a 12.56m diameter Herrenknecht Mixshield TBM plus an integrated package of support equipment to successfully drive

Recent slurry TBM bores in Gdansk were the key challenge to build a new road link. Report by Patrick Reynolds

the parallel bores, the first of which was executed in late 2013 and the second finished in June this year.

With ground conditions generally proving to be as expected, and pre-river stops being employed to replace worn tools, OHL completed the first drive 40 days (or more than 20 per cent) early – helped, too, by some modifications in concrete segment production. Learning from the first drive, the second bore achieved faster advance rates to finish even further ahead of schedule.

Piotr Czech, the FIDIC Engineer with the city's capital investment company, Gdanskie Inwestycje Komunalne (GIK), says: "The bores were easier than planned because we did not meet a lot of the risks that had been taken into account," – such as settlement, a precaution for which cranes were stopped as the TBM passed; and, the potential for displacement at riverside quays or fuel tanks in the industrial area.

From mid-year, as the shield and extensive system of slurry equipment were dismantled, construction quickly moved to the next stage of works in the tunnels – ground freezing for



cross passage construction; and, installing precast concrete base panels to form the road support structure and basement channels for services.

The Martwa Wisla road tunnel is due to be commissioned and in operation by the second half of 2015, says Czech.

## TRANSPORT NEED

Gdansk is a regional transport hub and needs to improve its road network. The "Slowacki Route" will help improve traffic connections between Lech Walesa Airport, in the west of the city, and the freight and ferry port.

The scheme is being achieved by a number of steps, including: increasing the share of environmentally friendly public transport; improving traffic safety; sections of upgraded road, and construction of new links – the most important, expensive and difficult of which is Martwa Wisla tunnel.

The entire "Slowacki Route" is being built by the city authority (Gmina Miasta Gdansk), through its subsidiary GIK. EU and local funds are co-financing the scheme, which is budgeted to cost a total of PLN 1.42bn (USD 430M).

The subsidy package from the European Union is in total PLN 1.15bn (USD 350M), which covers approximately 81 per cent of the entire project construction cost, according to Czech.

While Martwa Wisla tunnel is of 'paramount significance' to the city's goal, it is the fourth, and last, and most difficult, construction task on the "Slowacki Route". The other three projects are spread to the west of the city, and include a variety of road improvements and new road and bridge construction, and interchanges. The tunnel is at the eastern end of the scheme.

Located just on the north, coastal, side of the heart of the city, the tunnels cut below the Martwa Wisla shipping waterway.

Its bored tunnel section, however, accounts for only half of the 2.16km long underground link; there are also portal structures and long cuttings in the road link, which stretches from Przerobka on the east side of the river to Letnica in the west.

GIK says the "Slowacki Route" is 'hugely important' to improving traffic conditions in Gdansk, and to support 'further city development.'



## PLANNING & PROCUREMENT

Many options were considered to help the "Slowacki Route" cross the river. Alternatives ranged from building either fixed or draw bridges to constructing tunnels – and both immersed tube and bored tunnel were studied before the latter was chosen, says GIK's Piotr Czech. But while the bored tubes are not the longest of marine-environment tunnels, their construction challenge would be complicated by the soft wet ground.

Geology along the tunnel route comprises variable alluvial sediments of mainly medium and fine-grained sands with gravel and pebbles. Locally, at the river banks, there are silty sands, silts and clays. Deeper along the alignment, there are glaciofluvial sediments and moraine clays, both with boulders.

Groundwater level is high – approximately 600mm below the surface. Features of the groundwater are the high content of chloride and electrolytic conductivity, important to some ground freezing operations.

GIK's Piotr Czech says the hydrogeological conditions are the characteristic feature of the tunnel boring project.

As a result of the geological challenge, tunnellers opted to perform a major bentonite slurry TBM excavation.

The design layout spaces the tunnels 25m apart at their centrelines, and links them with seven cross passages, each 13m long. Each 11m i.d. tunnel will carry two lanes of traffic.

The chosen vertical alignment leads to overburden that, beyond the launch and exit portals, varies from 8m to about 21.5m over the crown. The applied design water level at the tunnel axis is up to 27.7m. Given the depth to be reached over a short distance, the

Above: Tunnel alignment within Gdansk, and location of Gdansk in Poland

Opposite: Aerial view of the project's worksite

## Patrick Reynolds

Patrick is a longstanding regular contributor to Tunnels & Tunnelling. He has a background in the mining industry.

gradients at each end of the tunnel are relatively steep – each four per cent.

Groundwater pressure at the deepest points of the tunnel alignment reach up to 3.5 bar, says GIK's Piotr Czech.

In addition to the bored section, the underground link also includes two other types of construction: portal structures, totalling 305m in length (192.5m, 112.5m); and, approach cuttings which have a combined length of 777.5m (630m, 147.5m). The longer approach is on the east (TBM launch) side of the river.

The Martwa Wisla crossing project also includes some other road construction, and the Marynarki Polskiej interchange just to the west of the tunnel.

Design was performed by two companies in consortium – Europrojekt Gdansk, and SSF Ingenieure GmbH from Munich, says GIK's Piotr Czech; GIK's own engineers are handling project management and construction supervision.

The main contractor leading on the tunnel works is OHL, which is head of a consortium, at the beginning of the contract, of . The contract began with OHL leading a consortium that included local firms PBG, PRG Metro, Hydrobudowa Polska and Aprivia.

GIK says the budget for this section of the "Slowacki Route" – covering the Martwa Wisla tunnel, road link and Marynarki Polskiej interchange – is PLN 885.6M (USD 268M).

The deep foundations subcontractor for OHL's contract package at Martwa Wisla is Keller's local subsidiary Keller Polska.

#### TUNNELLING EQUIPMENT

OHL contracted Herrenknecht to produce and supply a wide-ranging, integrated package of tunnelling equipment and systems to allow it to successfully execute the tunnel drives. The equipment includes: a single Mixshield TBM; the navigation system from VMT; a bentonite slurry system (separation plant and pumps); compressor station; formwork moulds to cast the concrete segments; and, manrider and materials transport.

The specification of the Mixshield TBM (S-745) includes a maximum torque of 16,841kNm, and nominal power of 3,500kW. To deal with the water pressure, the TBM had a triple brush seal and a quadruple sealing system between the skin of the shield and the installed segmental rings of the tunnel. The system was designed to enable the TBM to remain watertight



Above: Excavation of the tunnel approach on the river's far bank

under the increasing pressure while handling the relatively steep gradients at the beginning and end of the drives.

The segmental concrete lining design was for 2m long rings (6+key). In total, each of the twin bored tunnels has 538 rings, says GIK's Piotr Czech.

The slurry equipment included a HK60 mud mixer, a HSP2400 separator, centrifuge, mud tanks, pumps, pipelines and transfer system. Operating in manual or automatic mode, the HK60 could produce up to 40m<sup>3</sup>/hr of drilling mud.

The HSP2400 separator comprised a container (23m long by 9m wide by 10m high) with built-in double-deck vibrating screens and both pre- and post (fine) filters. The separator could take a spoil load of up to 500 tonne/hr (boulders, stones, gravel and sand) in the slurry.

GIK's Piotr Czech notes that the full plant system had a capacity of 2,400m<sup>3</sup>/hour of loaded slurry.

Factory acceptance of the TBM and support equipment was in September 2012, says Czech. The shield was then dismantled and prepared for transport from Germany to Gdansk, the final leg of the journey by ship which docked in the river near the project site. Re-assembly of the TBM and equipment began in November 2012.

The TBM was named "Damroka", after a 13th Century princess from the Gdansk region. Damroka was the daughter of Swietopelk II, the Great, who founded the church in Chmielno, inland from the city.

#### TUNNELLING

Foundation excavations began in Gdansk on the portal approaches with deep walls placed for a cut and cover section. TBM assembly began in late 2012 with tunnelling due to start in the second quarter of 2013.

The shield was officially launched in late May 2013. Excavation of the South Tunnel got underway in earnest in June, working three shifts per day, round-the-clock, five days per week. Precast concrete segments were cast at a factory in Kokoski.

By late August, having bored more than 450m (through sands), the shield approached a jet-grouted zone near the riverside quay at Nabrzeze Dworzec Drzewny. The concrete block was constructed to allow inspection and replacement of worn tools, under hyperbaric conditions, before the TBM proceeded below the river. Another would be available on the opposite bank, if needed.

Following the planned maintenance stop, boring resumed

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in mid-September and the TBM quickly reached the deepest part of the tunnel. All too soon the shield was beyond the river, boring below the quay at Nabrzeze Wislane and arriving at the west bank without the need for another planned maintenance stop in another jet-grouted concrete block.

The shield rapidly pushed through clays to close on the exit portal, completing the South Tunnel drive at the end of November. It had achieved progress rates of up to 122m per week.

Ground conditions were reasonably as anticipated, OHL and co-authors reported in a joint paper [1] to a symposium, held in February, on the tunnelling experience. They added, though, that there were more stones, pebbles and boulders than expected, and they were large – up to 350mm wide. They concluded, too, that the right choice of tunnelling equipment had been made for the ground conditions.

OHL's project manager, Jose M. F. Remesal, said in his paper [2] to the symposium that subsidence on the first bore had been less than three-quarters of theoretical design values. Subsidence was less than 50 per cent of expected levels for more than half of the drive. Bentonite consumption was 25 per cent less than expected, though the volume of grout needed for the annulus was a bit more than anticipated.

Power consumption was also much less than expected,

Below: Careful handling of the 12.56m-diameter Herrenknecht Mixshield



allowing a torque of only 30 per cent of the maximum, he said. It was anticipated that rather than consuming 24GWh for the drive, both tunnels might be excavated with only 12GWh.

The South Tunnel had an excavation programme of 183 days. The drive plan for the short bore was split into seven sections with advance rates between 4m/day-8m/day. Early on, average TBM progress during was approximately 6m/day on a 24-hour, five days per week basis, and edged higher, but was curtailed by the rate of segment production, he noted.

Adjustments were made to the concrete mix design to allow the mould to be stripped much earlier – achieving 25MPa strength after 8-10 hours instead of 24 hours. Curing time was also shortened by a quarter, from 28 days to 21 days, by when 95 per cent of total shrinkage would have happened.

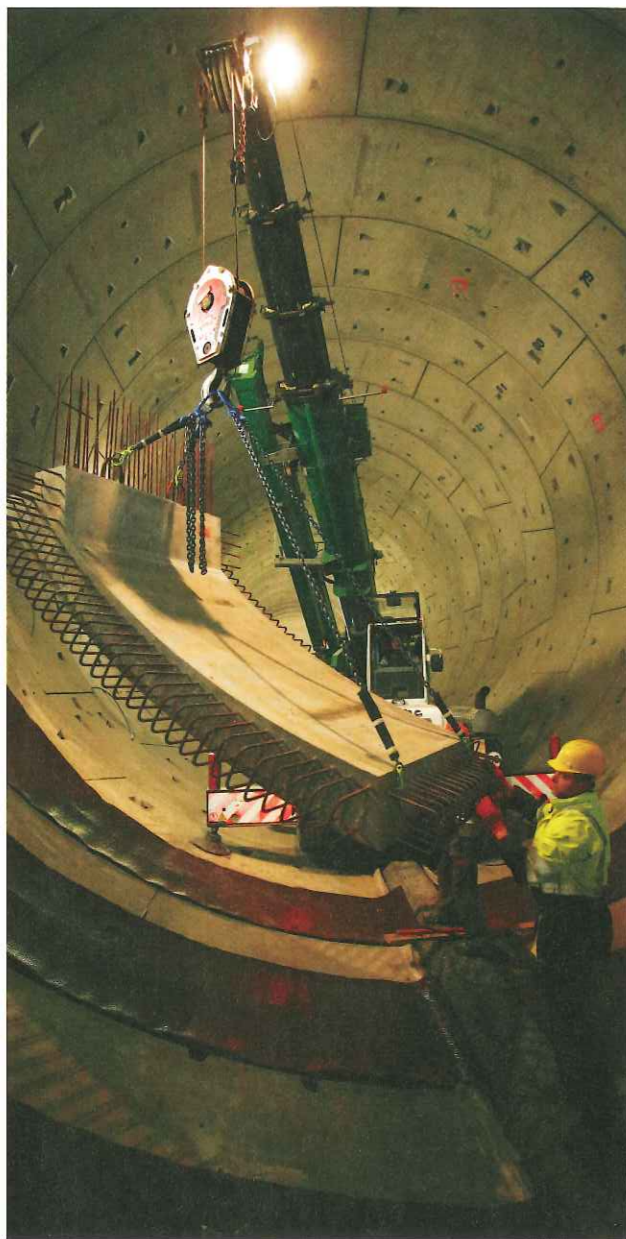
With the changes made, the contractor was able to build sufficient stock of segments during the TBM's two-week maintenance stop. When boring resumed, to drive below the river and then west bank, the changes enabled the advance rate to almost double to around 13m/day-almost 17m/day. The only challenge was having to slow to 6m/day, briefly, when passing through a clay zone, which increased the density of the bentonite slurry being carried for processing.

The first drive was completed in 143 days – 40 days ahead on the initial programme.

Higher progress rates – around 16m-18m/day – would be sought in the second drive, at the North Tunnel, working on seven days per week. The only slow stretch would be at the clay zone. Also, it was planned that the drive would start with a big enough stockpile of segments for about two-thirds of the length of the tunnel. It was anticipated that the tunnel's 183 day excavation programme might be beaten by around 90 days.

Preparing for the second drive, OHL dismantled and moved the shield back to the east bank during the darkest and coldest part of winter. Meanwhile, the backup equipment was pulled back along the South Tunnel, and switched over to line up with the North Tunnel. By the time the symposium took place, preparations were being finalised for the second drive.

OHL launched the shield again in early March, the concrete block was reached by early April, and soon the TBM was boring below the river. The drive was officially completed on 9



June, and tunnellers had achieved a best weekly advance of 132m.

While boring was underway on the North Tunnel, the contractor was busy in the South Tunnel installing the precast concrete structural slabs, walls and slabs

*Above:*  
Installation of segmental lining

to support the road platform, and house the utility services.

#### REMAINING TASKS

Since the end of TBM boring, and dismantling of the slurry shield and tunnelling support equipment, the follow-on works have focused on cross passage construction and further installation of the precast concrete elements for the road platform.

The cross passages are being constructed at intervals of about 175m along the tunnels, and two are below the river. They have excavated dimensions of 5.5m high by 5m wide, and finished cross sections of 3m high by 3.5m wide, says GIK's Piotr Czech.

OHL is working on the cross passages from the South Tunnel, performing extensive ground freezing at each cross passage location.

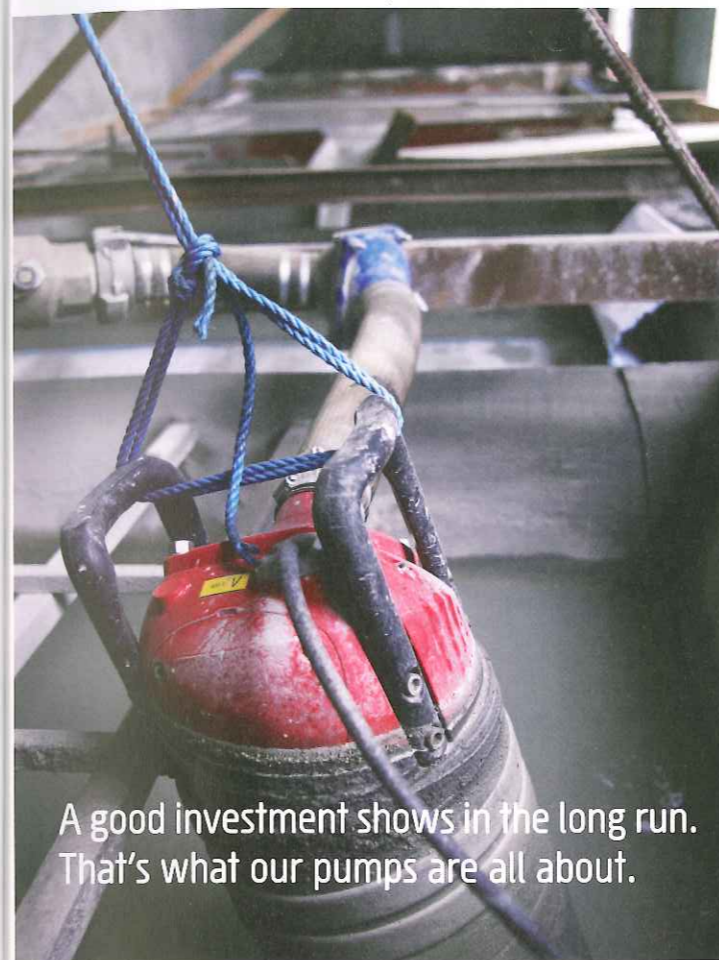
The treatment enables safe breakout from the main tunnel and excavation towards the other twin tube.

In the recently bored North Tunnel, works are focused on installation of the precast concrete elements for the road platform

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[2] Analiza dotychczasowej realizacji tunelu oraz zalecenia do wykonania drugiej rury tunelu i przejść poprzecznych (*Analysis of Tunnelling Works and Progress, and Recommendations for the Second TBM Drive*), by Remesal, J.M.F. February 2014, Symposium on Tunnelling at Martwa Wisla; Gdansk, Poland.



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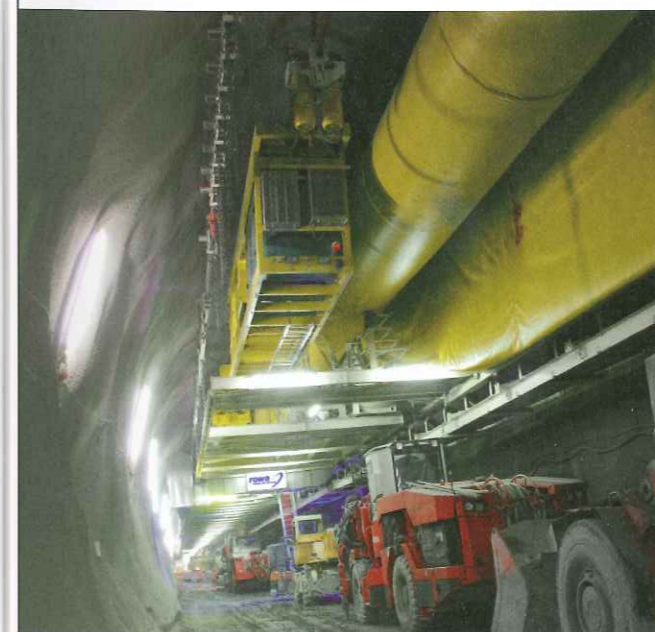
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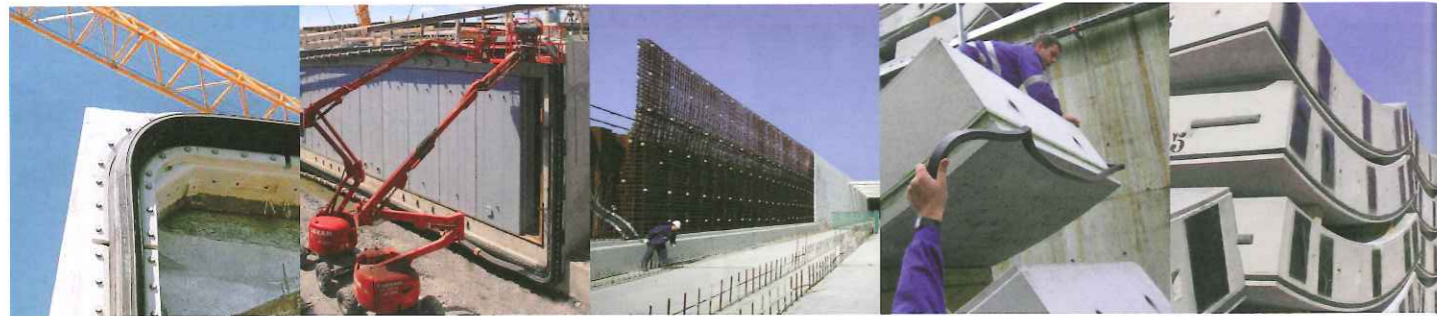
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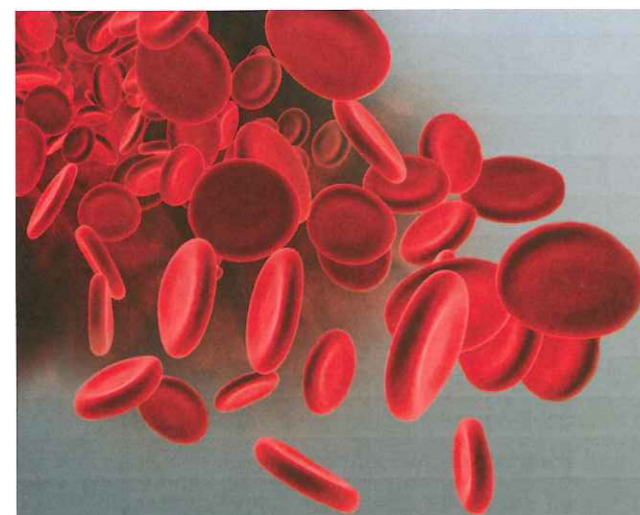
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# WARSAW METRO'S IMPROVEMENTS

Poland's capital Warsaw has two million inhabitants, but only one underground metro line. A second line, with 28 stations over 30km, is under construction. The central section of this line is being built under a turnkey contract awarded to the international AGP Consortium, made up of contractors Astaldi of Italy, Gulermak of Turkey and PBDIM of Poland. Italy's Rocksoil is providing technical assistance to the project, and here describes some of the challenges involved

**R**OCKSOIL'S ROLE on this project has been design and ongoing technical assistance on site during tunnel construction, driving the line tunnels and carrying out related works.

The central section of Line 2 is 6.3km long. It has seven stations between two terminus stations at Rondo Daszynskiego and Dworzec Wilenski. These twin bore tunnels are to be driven using four 6.3m diameter EPBMs.

A number of difficult underground passages have been identified along the route: between the Powisle and Stadion stations; under the Vistola River; and, under the two tunnels of Line One of the metro between the Rondo Onz and Swietokrzyska stations. Between Rondo Onz and Swietokrzyska, less than 3m separates the existing tunnels from those to be driven.

Last, but not least, in terms of complexity, is the passage under the new monumental complex of buildings in the "Prague" district between the Stadion and Dworzec Wilenski stations, discussed in this paper.

In this area remain Warsaw's only buildings undamaged by the bombings of the Second World War. Today, they are in a critical condition, due to poor

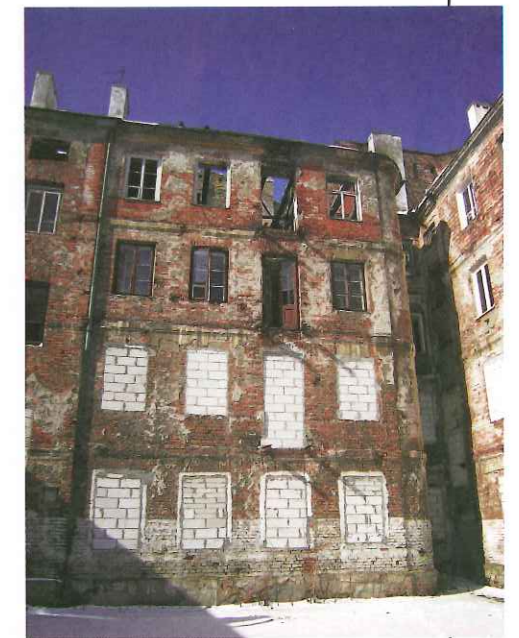
construction and maintenance.

The constraints of tunnel alignment meant that the tunnel needed to be designed to pass only of 6-8m beneath these historically important buildings' foundations.

Poland's Institut Techniki Budowlanej (ITB) was called in to conduct detailed structural analysis of the buildings. The ITB classified the buildings as at potential risk of collapse, even under normal conditions.

In order to reduce the risk connected with excavation to a minimum, the AGP consortium first designed and implemented structural intervention to protect some of these buildings, in preparation for the passage of TBMs. It also asked Rocksoil to develop a ground improvement plan that would take into account the fragile and historic nature of these buildings.

The geometry of the historic buildings and numerous other existing structure is extremely complex. The area includes extensive underground utilities, and only offers small surface spaces. This made it impossible to carry out the ground improvement treatment required using conventional methods. Recourse had to be made to complex construction technology in order to improve the



ground, forming an arch around the upper profile of the crown of the tunnels to be driven.

Given the large extent of the zone to be treated with ground injections, Rocksoil designed an innovative approach using "horizontal directional drilling" (HDD). This started from an

### Giuseppe Lunardi

Giuseppe is an MD for civil transport engineering at Rocksoil. He is heavily involved in the Italian Tunnelling Society

### Fabrizio Carriero

Fabrizio is a project manager and civil transportation engineer for Rocksoil, based in Rome, Italy

### Andrea Canzoneri

Andrea is a project manager for Rocksoil, based in Italy. He has a specialisation in ground freezing

### Maurizio Carini

Maurizio provides design and technical assistance on site as a Rocksoil engineer

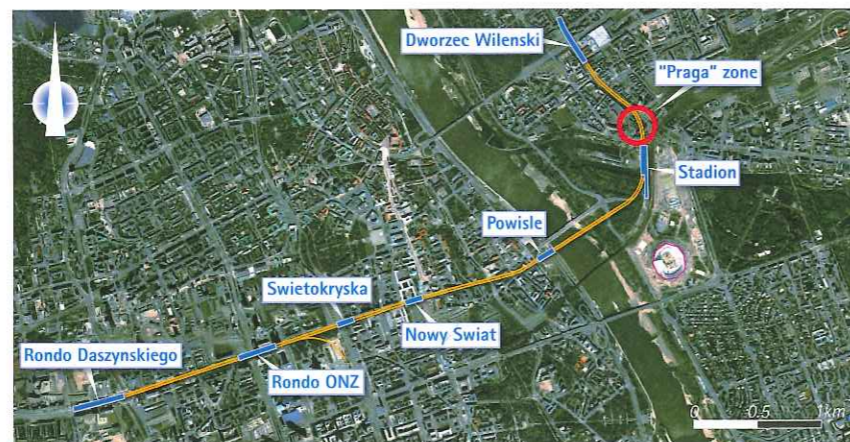
area relatively distant from the buildings, and gradually reached the correct depth around the tunnels to be excavated. These drillings were arranged parallel to the profiles of the future tunnels. They were designed to follow the tunnels for the whole 250m length of this section of the project.

The remaining part of this paper examines the design predictions generated by this new innovative technology and compares them with what actually happened during construction following TBM tunnel advance.

Design and construction was carried out on the basis of the principles of the ADECO-RS approach (Analysis of Controlled Deformation in Rocks and Soils) (Lunardi, 2006).

Which, as is known, employs the following stages:

- The survey phase: with the acquisition of information on the pre-existing equilibriums in the places in question (characteristics of the buildings affected by excavation, the geology and geotechnical characteristics of the ground, the natural stress-strain states, etc.);
- The diagnosis phase: numerical analyses are conducted in this phase, in the absence of ground improvement and stabilisation intervention, in order to assess the behaviour category of the ground's response to the action of excavation and the level of risk associated with each building;
- The therapy phase: this is based on the results produced during the diagnosis phase. The zones to be treated are identified and the ground improvement treatment is designed, by numerically assessing the beneficial effects that are sought, which would result in the behaviour of the ground's response to excavation being in category A (stable core-face) and place all the buildings in a damage class associated with a level of risk that can be considered acceptable;
- Operational phase and monitoring during construction: excavation and the intervention planned is carried out in this phase. The adequacy of the design is verified continuously and appropriate adjustments are introduced, which are nevertheless already allowed for in the design itself. The adjustments are based on the results of monitoring and then on the consequent back-analysis of the data.



Above: Figure 1, The central section of Warsaw Metro Line Two

### SURVEY PHASE

#### Geology of the places

The tunnel alignment of Line 2 runs through considerably heterogeneous ground. The ground directly affected by excavation consists mainly of alluvial deposits (sands and clays). The overburdens above the extrados of the crowns of the tunnels are between 10m and 14m, while the water table lies at between 4.5m and 8m. A description of the lithologies present in the zone in question is given in Table 1 and Figure 3.

#### Description of the monumental complex of the Prague area

Building in the monumental complex of the "Prague" district, affected by the passage of TBM's beneath it, dates back to the period between the end of the 1800s and the beginning of the 1900s. The main load-bearing structures of those buildings consist predominantly of brick masonry. Reinforced concrete structural components are present in some cases. The floors consist mainly of structural components in wood and steel, but rarely in reinforced concrete. The depth of the foundations varies between 3m and 4m beneath street level. Most of these buildings were affected by the devastation of the Second World War and were not rebuilt, except in sporadic cases, but above all they have not been maintained over the years. They have suffered the severe effects of the deterioration of the materials in the course of time. Past development of cracking, together with the deterioration in the materials has resulted in most of these buildings being classified as having non-ordinary structural behaviour. Furthermore, recent demolition of some bordering buildings and a fire, which affected part of these buildings, has further aggravated an already critical structural situation. In this context, in the more critical situations, it was

Table 1. Description of geological levels

Geological level	Description
VIII	Backfill soils
VI	Sands and clayey silts
Vb	Sandy clays and clays
IV	Gravelly sands and gravels
IIIa - IIIb	Medium and coarse sands
Ib	Fine and silty sands
Ib	Clays, silty clays and silts
Ia	Highly plastic clays

Source: Authors

Table 2. Structural intervention carried out before the passage of the TBMs

Building - number	Year of construction	Type of load-bearing structure	Initial condition	Structural Intervention Carried Out
Targowa 21 - 152	1890	Masonry	Critical Building uninhabited	Openings walled-up
Targowa 19 - 151	1910	Masonry	Critical Building uninhabited	Openings walled-up
Targowa 19 - 148				-
Targowa 17a - 149	1910-1913	Masonry and some reinforced concrete components	Cracking, deteriorated materials and lack of maintenance	-
Targowa 17a - 150				Steel chains
Targowa 17d - 146				Wooden beams around windows
Targowa 17d - 144	1928	Reinforced concrete	Cracking, deteriorated materials and lack of maintenance	-
Targowa 15 - 142				-
Zamoyskiego 27 - 137	1939	Masonry and some reinforced concrete components	Cracking, deteriorated materials and lack of maintenance	-
Zamoyskiego 27 - 129				-
Zamoyskiego 29 - 130	1910-1913	Masonry	Cracking, deteriorated materials and lack of maintenance	Steel chains and wooden beams around windows
Zamoyskiego 31 - 131	After 1945	Masonry	Cracking, deteriorated materials and lack of maintenance	-

Source: Authors

considered best to carry out structural intervention to protect some of the buildings (Table 2) in preparation for the passage of the TBM's.

This intervention made it possible to increase the coefficient of stability of the buildings considered most sensitive to excavation operations.

### DIAGNOSIS PHASE

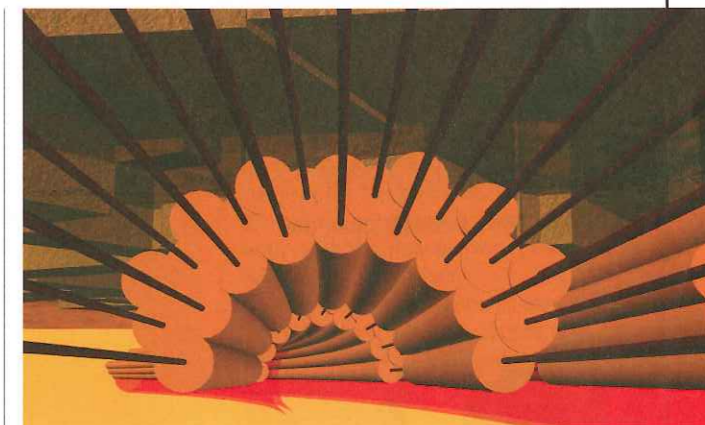
It is well-known that the excavation of a tunnel induces a change in the stress-strain state of the ground around the cavity, with consequent deformation which develops in the ground both longitudinally towards the tunnel face and transversely around the cavity. The consequent subsidence, which manifests on the surface, above all when the overburden is shallow, depends on the characteristics of the ground tunnelled, the position of the water table, the dimensions and depth of the tunnel, the excavation method employed and the speed of advance of the face (Anagnostou, 2008).

Both numerical and empirical methods were used to calculate the subsidence profile. Numerous experimental observations (Peck and Schmidt, 1969; Attewell and Farmer, 1974) show that surface subsidence curves can be represented well by a Gaussian normal probability function with two variables: the maximum subsidence  $w_{max}$  (along the centre line of the tunnel) and the distance  $i_0$  between the two inflection points of the curve, on which the width of the depression depends (Figure 4, page 36). The subsidence function can therefore be expressed by the following equation:

$$(1) w(x) = w_{max} \cdot e^{-\frac{x^2}{2i_0^2}}$$

Where:

$w(x)$  represents the subsidence at the abscissa  $x$ . The value of



Above: Figure 2, Soil treatment around the tunnel

$w_{max}$  can be obtained by establishing the expected volume of the subsidence depression, equal to the volume VP lost during excavation, i.e. volume of ground excavated in excess of the theoretical dimensions of the cavity. The volume lost is generally expressed as a percentage of the theoretical volume of the excavated tunnel,  $V_{tun}$ . In the case in question, a design assumption was made on the basis of values found in the literature for similar contexts, that VP would be equal to 0.60 per cent, which was confirmed as reliable by numerous back-analysis calculations carried out during construction.

In order to calculate the distance  $i_0$ , O'Reilly and New (1982) showed that when the size of the overburden above the crown of the tunnel is greater than

the diameter of the tunnel, a direct relationship can be assumed between the parameter  $i_0$  and the centre line of the tunnel  $z_0$  as follows:

$$(2) i_0 = K \cdot z_0$$

Where:  
the coefficient K is basically a function of the nature of the ground to be excavated.

In the case in question the coefficient K was assumed on the basis of values found in the literature to vary between 0.30 and 0.50 (respectively for sands and clays).

Once the depression and subsidence values were known, Burland & Wroth's theory (1974) was used to assess the resulting damage on the buildings by taking account of the following fundamental factors:

- The overall rigidity of the structure with the definition of the type of structure;
- The resistance to cracking of the materials of which the building is composed.

On the basis of experimental data, Boscardin & Cording (1989) correlated the expected damage to buildings with the values for the resistance to cracking of the materials on a scale of between 0 (negligible damage) to 5 (severe damage).

In terms of that classification, the



Left: A horizontal directional drilling rig

Table 3. Results of risk analysis in the absence of ground improvement operations

Building - number	Volume lost (%)	Maximum subsidence (mm)	Damage class
Targowa 21 - 152	0.60	20	2
Targowa 19 - 151	0.60	20	2
Targowa 19 - 148	0.60	13	1
Targowa 17a - 149	0.60	21	2
Targowa 17a - 150	0.60	22	2
Targowa 17d - 146	0.60	23	3
Targowa 17d - 144	0.60	23	2
Targowa 15 - 142	0.60	25	3
Zamoyskiego 27 - 137	0.60	24	3
Zamoyskiego 27 - 129	0.60	23	2
Zamoyskiego 29 - 130	0.6	26	3
Zamoyskiego 31 - 131	0.6	7	2

Source: Authors

damage class that was considered acceptable for the buildings in the Prague district affected by excavation operations for Line 2 of the Warsaw Metro was class 2, corresponding to slight damage with modest and easily repairable cracking being identified.

Risk analyses developed on the basis of the classic theories just described produced the results reported in Table 3.

### THERAPY PHASE

#### Design of operations with horizontal directional drilling

In order to reduce the risk level for the buildings in the "Prague" district to damage class 2, protective ground improvement operations were designed in the therapy phase, which not only improved the mechanical characteristics of the ground around the future excavation, but was also able to reduce the probability of foam leaking during TBM advance, with significant loss of volume and unpredictable subsidence on the surface as a consequence.

The intervention consisted of improving a circular section of ground above the crown of the excavation with a thickness of approximately 3m and a length equal to that of the passage beneath the buildings concerned.

The operations were particularly complex and unusual because of the length of the drilling required (250m) and the minimum radii of curvature of 100m and 300m for single or double curvatures respectively. In addition to the foundations of the buildings the ground treatment also involved a large sewer locally.

Valved PVC tubes were inserted in the drillings through which cement mixtures and appropriate chemicals were injected into the ground by permeation between the profile of excavation of the tunnels and the buildings above in order to produce the necessary increase in its mechanical properties.

On the basis of assessments carried out on similar ground treatments performed in grounds similar to those in question, it was considered reasonable from a design viewpoint to assume a Young's modulus of 2.5 times that of the natural ground for the treated ground.

In order to assess the effects of the treatment on the risk

Table 4. Results of risk analysis in the presence of ground improvement operations

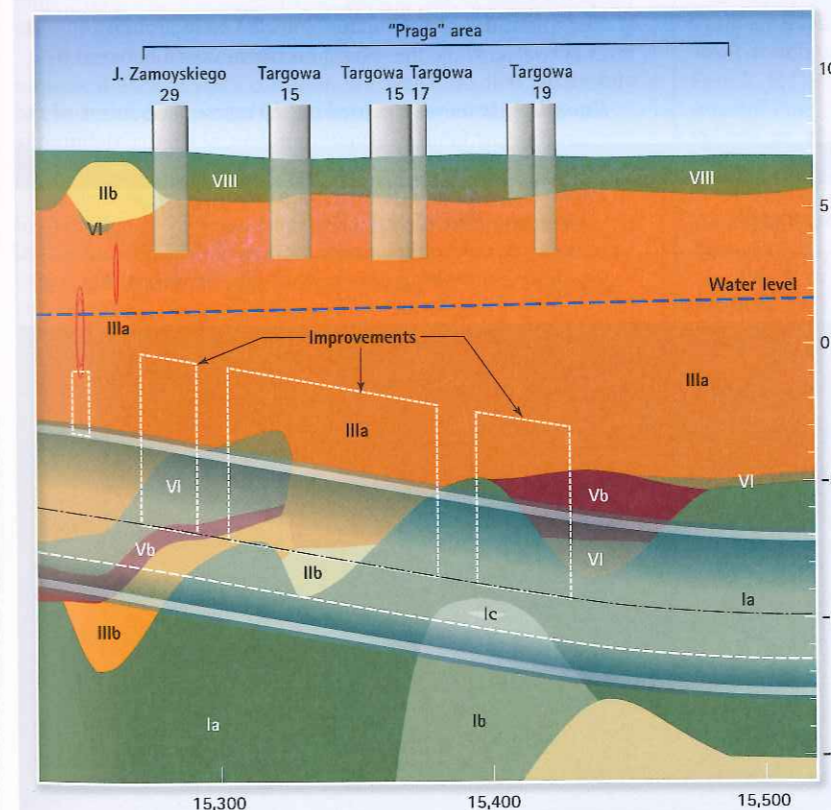
Building - number	Volume lost (%)	Maximum subsidence (mm)	Damage class
Targowa 21 - 152	0.44	15	2
Targowa 19 - 151	0.44	14	2
Targowa 19 - 148	0.44	10	0
Targowa 17a - 149	0.44	15	2
Targowa 17a - 150	0.44	16	2
Targowa 17d - 146	0.44	17	2
Targowa 17d - 144	0.44	17	2
Targowa 15 - 142	0.44	18	2
Zamoyskiego 27 - 137	0.44	17	2
Zamoyskiego 27 - 129	0.43	17	2
Zamoyskiego 29 - 130	0.43	18	2
Zamoyskiego 31 - 131	0.43	5	1

Source: Authors

levels, both numerical analyses were developed using the Itasca FLAC finite differences calculation programme, and empirical methods were derived from the classic theories described previously:

- The theoretical reduction in the volume of ground lost was assessed using the FLAC analyses and empirical methods;
- Once the expected values for lost volumes were known, the risk analyses were carried again out using the same criteria as those reported earlier

Below: Figure 3, Underground situation of the Prague district



Simulations of the different stages of tunnel excavation were carried out using two dimensional FLAC analysis, replacing the ground excavated with equivalent forces, which were gradually reduced as a percentage to reproduce the effect of tunnel advance. Ground improvement was simulated by increasing Young's modulus by 2.5 times the values for the natural ground.

The first numerical step was to calculate the percentage reduction of the excavation forces under free field conditions and in the absence of ground improvement, in order to obtain the congruence between the theoretical subsidence curve (with  $V_p=0.60\%$ ), obtained using classical methods and that calculated by using FLAC iteration analyses.

FLAC analyses were then carried out in the presence of improved ground, with the percentages of the excavation forces determined in this manner.

Finally, the percentages of the volume of ground lost were determined in the presence of ground improvement, comparing the subsidence depression calculated using those analyses with those calculated using empirical methods.

The percentages of volume lost determined in this manner were reduced by approximately 30 per cent compared to the value of  $V_p=0.60$  per cent in the absence ground treatment. The risk analyses for the buildings under which the tunnels were to pass were calculated again with the new percentages for the volume of ground lost.

A significant reduction in expected subsidence and damage classes was seen, with the latter all within class two (see Table 4) following the ground improvement.

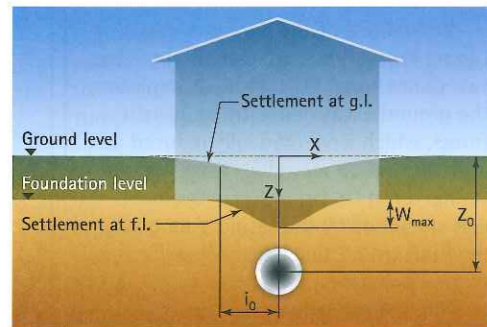
### OPERATIONAL PHASE AND MONITORING DURING CONSTRUCTION

#### Operations using horizontal directional drilling (HDD)

Ground improvement was carried out by the Italian contractor Icotekne using low pressure injections of cement and chemical mixtures, after first performing HDD.

This technology was used to achieve a controlled route by using a special asymmetrical drill bit with an angled surface which is piloted by an external magnetic localisation system by which the direction of the drilling could be guided as it advanced.

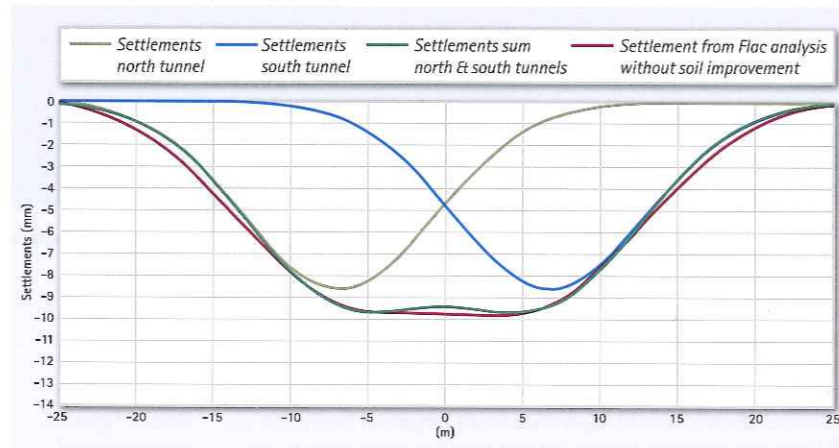
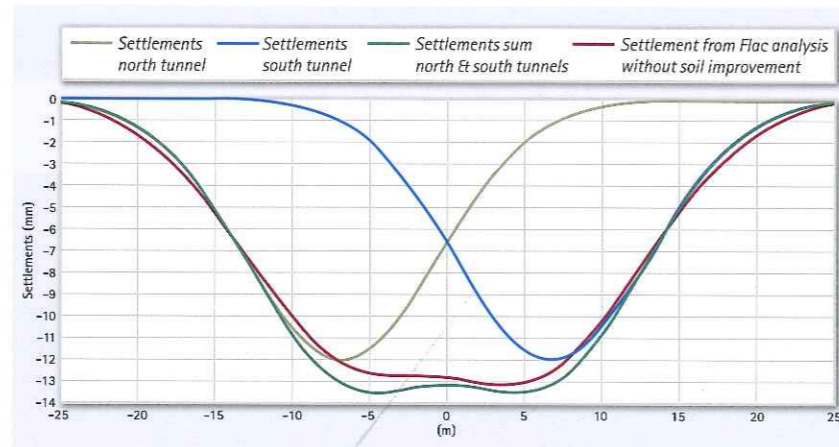
The tolerances were well within acceptable ranges (a few centimetres,



despite the long lengths to be drilled and the short radii of curvature). In order to minimise the risk of local collapses, the bore was fitted with an appropriate steel lining.

The operation was carried out in the following stages:

1. Placing of electric cables on the surface to generate the magnetic field for the directional control of the drillings;
2. Drilling and subsequent installation of the preliminary steel lining with a diameter of 140 mm;
3. Insertion of a valved injection tube (two valves per metre) in PVC (diameter of 2in) inside the steel tube;
4. Execution of the primary sheathing injection using the cement mixtures and extraction of the steel lining at the same time. The injection of the sheathing at this stage replaces the preliminary steel lining;
5. Repeated injections of cement mixtures and chemicals at controlled pressures and volumes.



Top left: Figure 4, Subsidence depressions at street level and foundation level

Type 52,R microfne cement grouting was used to facilitate the permeation of the cement mixtures.

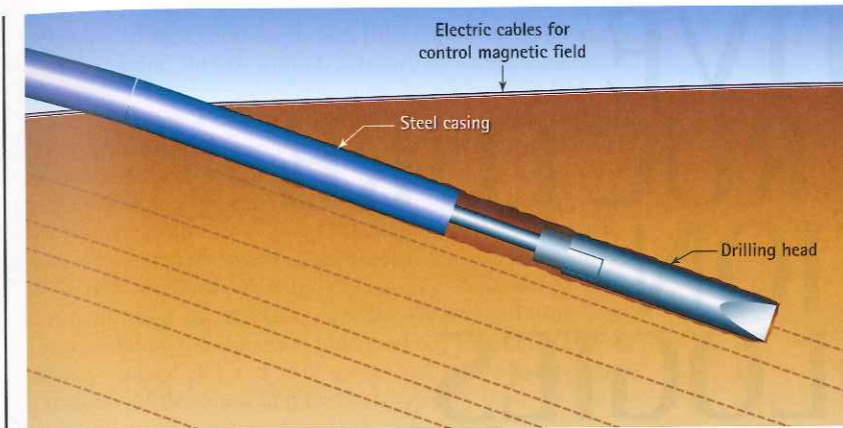
The quantities of the mixture injected were around 110-120 litres per valve, while the refusal pressures varied between 8 and 12 bar.

Cross-hole tests were carried out to assess the success of the

Table 5. Comparison of volume lost and subsidence

Building - number	Diagnosis Phase		Therapy Phase		During Construction	
	V <sub>p</sub> (%)	W <sub>max</sub> (mm)	V <sub>p</sub> (%)	W <sub>max</sub> (mm)	V <sub>p</sub> (%)	W <sub>max</sub> (mm)
Targowa 21 - 152	0.60	20	0.44	15	0.41	8
Targowa 19 - 151	0.60	20	0.44	14	0.38	8
Targowa 19 - 148	0.60	13	0.44	10	0.38	7
Targowa 17a - 149	0.60	21	0.44	15	0.26	7
Targowa 17a - 150	0.60	22	0.44	16	0.26	6
Targowa 17d - 146	0.60	23	0.44	17	0.26	6
Targowa 17d - 144	0.60	23	0.44	17	0.26	6
Targowa 15 - 142	0.60	25	0.44	18	0.30	5
Zamoyskiego 27 - 137	0.60	24	0.44	17	0.31	5
Zamoyskiego 27 - 129	0.60	23	0.43	17	0.43	9
Zamoyskiego 29 - 130	0.60	26	0.43	18	0.43	9
Zamoyskiego 31 - 131	0.60	7	0.43	5	0.43	4

Source: Authors



Above: Figure 7, Drilling stage and insertion of the preliminary lining

Opposite (graphs): Figures 5 and 6, Comparison of results using empirical methods and FLAC analysis in the absence of ground improvement

treatment.

These confirmed the accuracy of the value that was adopted in the numerical analyses, with an increase in the Young's modulus of the improved ground, E<sub>impr</sub>, compared to that for the natural ground, E<sub>nat</sub>:

$$(2) E_{impr} = 2.5 \cdot E_{nat}$$

#### Stable tunnel advance with EPBMs

Two EPBMs were employed to drive the tunnels, capable of controlling subsidence of the ground by adjusting the operating parameters of the machine.

More specifically, the main parameters defined in the design and 'controlled' during construction were those relating to the stabilisation pressure in the excavation chamber and the backfill pressure of the grout injections behind the concrete segments.

To achieve this a complex system of topographical monitoring was designed and put in place in preparation for tunnel advance operations, based on readings of ground pins, mini prisms and levelling pins installed on the buildings above the tunnel.

The results of the monitoring were used to carry out numerical back analysis continuously, which made it possible to check the design machine parameters in real time and take appropriate corrective action promptly in order to conform to safety requirements.

Table 5 shows the percentages for volume lost and values for subsidence forecast at the design phase (diagnosis phase in the absence of intervention, therapy phase in the presence of ground treatment) and those measured during actual construction.

As can be seen the percentages of volume lost measured during construction were either in line with or below the theoretical values predicted by the design.

The result was the same for the maximum subsidence values observed. The width of the subsidence depressions recorded during construction were greater than those predicted theoretically.

This fact falls within the norm, because the numerical analyses conducted during the diagnosis and therapy phases were carried out under free field conditions, i.e. not taking account of interaction between the ground and the structure.

Therefore the real distribution of movements recorded during construction showed, as it was reasonable to expect, a better final configuration than that predicted by the design. The excellent results achieved confirmed the validity of the treatment employed and that it was properly executed.

Maintaining the percentages of lost volume recorded below those predicted by the design was the result of the proper and

very efficient execution of the excavation operations.

In this respect, good levels of production were recorded, sufficient to ensure that the machines remained below the complex of monumental buildings for a limited period of time, while passing beneath them.

#### CONCLUSIONS

Rocskoil designed an innovative method to improve ground, with horizontal directional drilling of 250m in length, and with a short radii of curvature for the difficult task of driving a tunnel beneath the complex of monumental buildings in the Prague district of Warsaw, consisting of numerous historical buildings in precarious conditions of stability.

The operations were carried out well and together with the survey carried out by the AGP Consortium's TBM team, this made it possible to drive a tunnel beneath the district under safe conditions and in full compliance with the design specifications.

The success of the operation is borne out by the results of the monitoring performed during construction, which showed volumes of ground lost in line with or below those predicted by the design. The maximum subsidence recorded by the teams was always less than that predicted.

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# INNOVATIVE INFRASTRUCTURE INSPECTION TECHNOLOGIES

With aging infrastructure becoming a common problem throughout the United States, time efficient and innovative inspection technologies are needed in order to facilitate infrastructure inspections that can be done rapidly and in-depth with minimal impact to infrastructure operation as cost-effective as possible

THE UNITED STATES INFRAS-  
TRUCTURE is in desperate need of repair and upgrading. ASCE's Report Card For America's Infrastructure released in March 2013 gave an overall grade of D+ (p.3, DiLoreto) across 16 categories in comparison to a D given in ASCE's 2009 Report Card. Although an improvement, a D+ is nothing the current richest and most powerful country in the world should brag about. And yet with the consistent low grading of America's infrastructure systems, owners are specifying old technologies in their Tunnel Inspection RFP's including recent examples in Pennsylvania and Oregon.

Like the personal computer so has infrastructure inspection technology advanced and yet these new technologies are not being specified by owners. This paper will examine innovative inspection technologies and hopes to open a dialogue with infrastructure owners and government agencies like the FHWA and its National Tunnel Inspection Standards (NTIS), which are currently being developed and are close to becoming required.

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## 3.1k

The estimated cost, in USD to "American families" if a preemptive approach to infrastructure maintenance is not adopted, according to ASCE

And not only should new technologies provide more in depth information, but inspection systems should also be developed that have minimal impact to the infrastructure's operation. The inability to shut down infrastructure is often why infrastructure inspection is delayed due to the inability to close down a Tunnel or a Bridge for more than five hours in the middle of the night or the inability to shut down at all such as critical drinking water supply lines like the San Francisco Public Utilities Commission's Old Irvington Tunnel.

The key aspects new inspection technologies need to provide are as follows:

- Minimises impacts to operation
- Provides comprehensive condition assessment
- Allows comparison to future inspections to measure the change in condition
- Allows inspections to be safely performed
- Cost effective

## NON-DESTRUCTIVE TESTING AND RAPID SCAN SYSTEMS

In recognition of the issues discussed above, the Transportation Research Board's SHRP 2 program has funded a research program titled 'R06(G) Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects behind Or Within Tunnel Linings' being headed by Texas A&M University. This paper will not cover this study in depth as this studies own reports, but will give the reader of this paper valuable information on the inspection technologies being evaluated and studied under the R06(G) research project.

One of the main goals of the SHRP 2 study is the development of both rapid screening and in-depth inspection whereby rapid screening is first completed, which helps identify areas of greatest concern which are then inspected with the slower in-depth methods. The performance criteria that was set by the expert panel for both the rapid screening and in-depth methods established that the NDT methods should detect a defect within, or immediately behind the tunnel linings that have a minimum surface area of 1ft<sup>2</sup> (0.09m<sup>2</sup>) and any defect needs to be located within 1ft of the actual location on the tunnel lining. Additionally, NDT methods should identify

delaminated area voids up to 4in (101.6mm) deep as measured from the lining surface with an accuracy of within 0.25in (6.35mm).

To determine which NDT methods meet this criteria, the SHRP 2 research team conducted research on the Eisenhower Memorial Tunnel, Hanging Lakes Tunnel, and No Name Tunnel in Colorado, the Chesapeake Channel Tunnel in Virginia, and the Washburn Tunnel in Texas to study tunnels constructed with different methods. All three tunnels in Colorado were built using drill and blast, while the Chesapeake Channel Tunnel was built using cut and cover, and the Washburn Tunnel was constructed by the immersed tube method. Therefore their subway covered all but a TBM tunnel and therefore represents a majority of the tunnelling methods typically used. All five tunnels use tile over their final lining, also known as tile concrete which is typical of highway tunnels.

The following in-depth and rapid screening techniques were able to meet the criteria set in the SHRP 2 study and are briefly described below:

- **Air-coupled ground penetrating radar (GPR):** Uses discrete electromagnetic pulses sent into a structure and then captures the reflections from layer interfaces in the structure. At each interface within the structure, part of the energy is reflected and part of the energy is transmitted. This difference is used to calculate the layer thickness and dielectrics. Defects can only be detected if significant moisture or air pockets are within the defects.
- **Thermography (handheld thermal camera):** Uses significantly improved thermal cameras to capture temperature differences within the lining possibly indicating defects within or behind the lining.
- **Tunnel scanner (discussed in detail below):** Uses photogrammetry and or terrestrial laser scanning to capture surface conditions and insitu geometry.
- **Ground coupled GPR:** Similar physical phenomena as Air Coupled GPR except needs to be in contact or very close to the lining surface when data is being collected. The difference is ground coupled GPR can detect more accurately and can also detect rebar.
- **Ultrasonic tomography:** Uses an array of ultrasonic transducers to transmit and receive acoustic stress waves which are then converted into a three dimensional volume with a digitally focused algorithm. The intensities of the returned waves are colour coated to show discontinuities (voids, cracks, delaminations etc) with distinct wave speeds.
- **Ultrasonic echo:** Uses an ultrasonic transducer to send and receive ultrasonic pulses from the same side of the test object by the same or two separate transducers which is then measured to locate discontinuities and the thickness of the object.
- **Portable seismic property analyser (PSPA) ultrasonic surface waves and impact echo:** Ultrasonic surface waves use the time difference in surface wave propagation to determine the modulus. The differences in velocity with wavelength are then used to generate a dispersion curve whose variation in velocity identifies discontinuities. Impact echo uses the stress waves generated by impact then converted into a frequency domain by a fast Fourier transform algorithm to detect changes in amplitude and shape of the frequency curve to indicate discontinuities. Both of these methods are simultaneously conducted with the SPA using a solenoid-type impact hammer and two high-frequency accelerometers.

Some of the methods above are for use in rapid scanning

and some for more in-depth scanning. Therefore, based upon the goal to perform a rapid initial scan then followed by an in-depth scan of specific areas identified, the following procedures were suggested by the R06(G) research team (p.5, Wimsatt et al):

1. "Collect thermal images and air coupled GPR data on the tunnel lining. Air coupled GPR data should be collected every foot along the tunnel lining. Thermal images can be collected every foot as well; however, the equipment covered in this report can collect data at a spacing determined by the camera operator or tunnel inspector. This data should be collected ideally on the same day; however, it can be collected separately. The thermal images should be collected when the air temperature is rising or falling; areas of possible defects may show up better in the thermal images. The data from any of these devices can be obtained at a waling pace (around 1mph [1.61kph]). Air coupled GPR data can be obtained at much higher speeds, but the geometry and features in tunnels may make it difficult to operate the equipment at speeds much greater than 1mph.
2. Analyse the data from the scanning devices above. Select areas for in-depth testing based on the GPR surface dielectric results, thermal images, and observed surface distresses that are of concern to tunnel inspectors.
3. Conduct in-depth testing with the ground coupled GPR and either the ultrasonic tomography, ultrasonic echo, or portable seismic property analyser device. The choice of equipment could be based on the cost and the type of defect to be detected (tile debonding, delaminations, and voids). The ultrasonic tomography and ultrasonic echo devices may be more appropriate for measuring and mapping defects greater than two inches from the tunnel lining surface. The ultrasonic tomography device is more expensive than the other two devices; however, it has the capability to provide more information in the field about such defects. The portable seismic property analyser may be more appropriate for determining the limits of shallow defects.
4. Evaluate the data collected from these devices."

Additionally, Table 1 was provided

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A world of information fully archived and searchable at the click of a mouse



Table 1. Summary of NDT devices

Device	Accuracy	Detection depth
Air-coupled ground-penetrating radar (GPR)	Locates defects within 1ft of actual location	Does not measure depth, but indicates areas of high moisture or low density (high air voids). Such areas may represent problems within or behind the tunnel lining.
Thermography (handheld thermal camera)	Locates defects within 1ft of actual location	Does not measure depth, but can indicate tile debonding, delaminations up to 1in, voids up to 3in.
Spacetek scanner	Locates defects within 1ft of actual location	Does not measure depth, but can indicate tile debonding, possibly delaminations up to 1in, and possibly voids up to 3in.
Ground-coupled GPR	Can determine defect depth within 10% of the actual depth without reference cores, 5% if cores are available	The device can possibly detect defects at any depth within or immediately behind tunnel linings. However, specimen testing indicates it cannot locate 1sq.ft voids in steel plates behind tunnel linings
Ultrasonic tomography	Concrete: voids within 0.5in, shallow delaminations within 0.75in, shotcrete: air filled voids within 0.7in, water-filled voids within 1.21in, shallow delaminations within 1.38in	Can detect defects up to 8in deep based on specimen tests. Tunnel tests indicate it can detect possible defects up to 20in deep.
Ultrasonic echo	Comparable to the ultrasonic tomography system based on tunnel testing with both devices. Past experience indicates also it can measure tunnel lining thickness with 3% of actual	Comparable to the ultrasonic tomography system based on tunnel testing with both devices.
Portable seismic property analyser (PSPA) ultrasonic surface waves and echo	Ultrasonic surface waves: about 15% of the actual depth for defects of up to 6in deep. Impact echo: 10% for deep delaminations greater than 6in deep.	Ultrasonic surface waves: up to 6in deep. Impact echo: up to 18in deep.

by the R06(G) research team (p.3-4, Wimsatt et al) for each of the methods tested outlining key information for each method.

**TUNNEL SCANNING SYSTEM**

Three-dimensional imaging in tunnels is becoming a valuable NDT tool for gaining accurate and comprehensive information of the condition of the tunnel lining surface. Although this technology does not allow seeing what is behind or within the tunnel lining, it does provide high-resolution 3D images of common deficiencies such as cracks, spalls, or leakage on the surface, in relation to the tunnel alignment and stations. By performing a tunnel scan as a first inspection measure, the overall condition of the tunnel surface can be documented and the data used to locate visible deficiencies on the surface. These detected deficiencies and their locations are stored in a deficiency database and can be effectively used as a baseline for further NDT. The advantage of performing a tunnel scan over a manual visual inspection lies in the quality of information gained from the scan data as well as overall time and personal savings. Both of these

advantages relate to ageing infrastructure because often high quality information on the ageing infrastructure is lacking or not available and shutdown time and inspection costs are always needed to be kept to a minimum.

Terrestrial laser scanning is on its way to become one of the standard technologies for object acquisition in surveying engineering. The possibility to obtain a dense three-dimensional point cloud of the surface of the object under investigation immediately excels other traditional surveying techniques. Combining the high spatial resolution of photogrammetric imaging with the excellent capability of measuring 3D space by laser scanning bear great potential for both data acquisition and compilation. With the help of such a hybrid scanning system which combines lidar and photogrammetric technology, it is possible to obtain an accurate point cloud and high resolution digital images simultaneously resulting in a true colour rendered 3D scan model. This technology can be very well utilised for tunnel inspections, as it delivers a comprehensive and dense illustration of the tunnel surface. State of the art software allows performing a virtual inspection from the desktop generating tunnel maps and inspection reports in a more detailed way than ever before.

Two types of tunnel scanning systems that utilise hybrid sensor technology have proven to be very effective for road and rail tunnel inspections. The more traditional way of scanning is the stop and go, or more commonly known as static scanning method. The heart of this system consists of a terrestrial laser scanner utilizing the time-of-flight measurement principles. The scanner emits an infrared laser beam which is moved in a plane by a rotating mirror, resulting in a dense cloud of points. The success rate of laser scanning depends on the reflectivity of the surface. Common materials used for tunnel lining (i.e.

Deterioration mechanisms detected	Tunnel lining types	Other information
Tile debonding, delaminations, air filled voids, water filled voids, moisture intrusion	Concrete, tile-lined concrete, and shotcrete	This is a scanning tool that can indicate where to conduct testing with in-depth devices
Tile debonding, delaminations, air filled voids, water filled voids, moisture intrusion	Concrete, tile-lined concrete, and shotcrete	This is a scanning tool that can indicate where to conduct testing with in-depth devices
Tile debonding, delaminations, air filled voids, water filled voids, moisture intrusion	Concrete, tile-lined concrete, and shotcrete	This is a scanning tool that can indicate where to conduct testing with in-depth devices. Testing can only be conducted through a service contract.
Delaminations, air filled voids, water filled voids, moisture intrusion	Concrete, tile-lined concrete, and shotcrete	Experienced personnel are needed to interpret defect locations and depths from the GPR scans. Specimen testing indicates it cannot locate 1sq.ft voids in steel plates behind tunnel linings.
Delaminations and voids	Concrete, tile-lined concrete, and shotcrete	May not be effective for measuring defects that are 2in or less from the lining surface. May not be accurate enough for measuring defect depths in shotcrete.
Delaminations and voids	Concrete and shotcrete	May not be effective for measuring defects that are 2in or less from the lining surface. May not be accurate enough for measuring defect depths in shotcrete. Tunnel tests indicated problems with using this device on tiles.
Delaminations and voids	Concrete, shotcrete and tile-lined concrete	May be difficult to quantify the depth of defects that are shallow or extensive. May not get good results when testing on very rough concrete surfaces, oily surfaces, and severely curved surfaces.

concrete, shotcrete, tiles) or just rock tunnels have proven to be well suited for laser sensors. The instrument as shown in Figure 1 as an example is the Riegl LMS Series, which is tilted 90 degrees to enable more efficient data collection in tunnels.

By aligning the scanner axis with the tunnel axis, data can be collected through 360 degrees in the form of individual rings or sections rather than spheres. The static scanning system is positioned close to the tunnel centre line and moved along it, scanning sections of the tunnel with each setup. At the end, multiple scans from each setup are merged together to form the 3D point cloud. Scan data registration and geo-referencing occurs through reflective targets that are positioned on the instrument and in the view of the sensor. This method is called indirect geo-referencing. Reflective targets are detected on the scan and assigned with their coordinates in a local scanner based coordinate system. A total station is then used to measure every target of each setup and obtain their spatial coordinates in the external coordinate system. Through a procedure called geo-referencing, the registered scans are transformed from the scanner based local coordinate system to an external (geodetic) coordinate system. This allows the scan data to be integrated into other geospatial data.

The stop and go system has been used very successfully in road tunnels but can also be adapted to rail tunnels with a platform that can be pushed along rail tracks. The data acquisition rate depends on how much tunnel can be scanned with one setup and how fast the targets can be measured for each scan. Due to a fully automated target measurement process and a robotic total station, which remotely obtains the coordinates of each of the scanner targets, the time for one scan can be as fast as three minutes. A point accuracy of 5mm can be achieved using this method of measured points on

Right: Figure 1, Example of stop and go (static) scanning system

Right, below: Figure 2, Example of kinematic scanning system



the tunnel surface in relation to tunnel control points.

The second hybrid scanning system used for tunnel inspection is a more recent development with a different and more advanced data collection approach than the stop and go scanning method. This system is based on the kinematic laser scanning method as opposed to

static terrestrial laser scanning. During kinematic laser scanning, the system changes its position during the data acquisition and therefore scans the tunnel surface from a moving position.

The system is installed on a rail vehicle, hand pushed by the operator. A dense array of data is acquired as the scanner is walked along the tracks recording detailed information of visible defects on tunnel linings. The heart of the kinematic system is a phase shift laser scanner with a 360-degree sensor view. The instrument as shown in Figure 2, as an example, is the FARO scanner. The scanner emits an infrared laser beam, which is moved in a plane by a rotating mirror. The results are transversal profiles. From the forward motion of the rail vehicle, a 3D point cloud forms in the appearance of a line rather than a sphere, hence the term line-scanner. This method of scanning differs in a way that there are no single scans that have to be registered in the end to complete the scan model. The line-scanner collects one continuous data stream during a steady movement of the platform. The number of data points is dependent on the acquisition rate of the laser scanner, the rotation rate of the deflection system, and the velocity of the platform. Additionally, a signal intensity value provides information about the reflectivity of the surface at each target point. The kinematic system also includes an odometer to measure the trajectory of the moving platform and a tilt sensor for the determination of the system's 3D state. The data of these sensors is stored in a data logger, which is used for scan orientation. The scans of a kinematic system are oriented relative to the existing tracks and can be accurately referenced to tunnel stations. Therefore no control points and reference targets need to be installed, which eliminates additional time spent for target measurement by a total station. Instead, the rail track centerline serves as a baseline and for scan registration. The absolute achievable accuracy after



Above: Figure 3, Scan data processing stages. Form point mesh to laser intensity image to true colour rendered scan model

Below: Figure 4, True colour rendered scan model of a road tunnel



adjustments in 10mm.

The obvious advantage of the kinematic system is its high scanning speed. This comes into play in tunnels with high frequency traffic such as subway tunnels in which complete shutdown times have to be held at a minimum. Past projects have proven that a distance of 1 mile (1.6km) can be scanned in just three hours, which is significantly faster than using a static scanning system. In addition to the laser scanner, digital cameras are installed on the scanner or in the case of the kinematic system, on strategic locations on the platform. This enhances the quality of the final scan model in terms of rendering the point cloud using high resolution imagery obtained during scanning. Digital SLR cameras are configured to capture overlapping pictures automatically during scanning.

### DATA PROCESSING

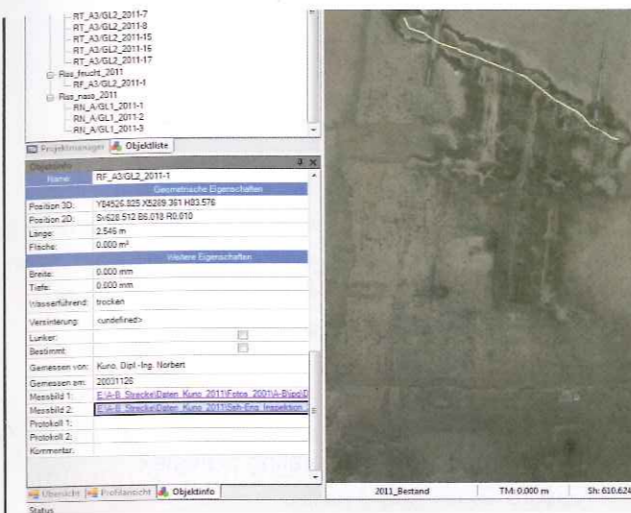
The type of data acquisition method of hybrid scanning systems provides dense three-dimensional point clouds and high-resolution images. The first step to recreate the tunnel digitally is to build a reference model based on design drawings including alignment, profile and the typical cross-section of the tunnel. The 3D registered point cloud and surface reflectivity values from the laser scanner are projected onto the reference model. For the image registration, stereo matching occurs. The registered images are then aligned with the laser scanner data and refined through data point matching between the laser reflectivity texture and the digital images. The result of this process is a complete 3D model of the tunnel surface, rendered in high-resolution images (see Figure 3).

### DATA ANALYSIS AND MAPPING

Increasingly faster computer technology enables software to handle high-density data and load the rendered scan model in real-time. This allows the engineer to virtually walk through the tunnel and observe, investigate and analyse the state of the tunnel lining surface in a 3D environment. This means that a tunnel inspection can be done from the desktop and a pre-inspection overview can be made. The user can virtually walk along the tunnel alignment or in a free 3D orbit mode always in reference to the actual tunnel stations. It is also possible to compare initial and follow-up scans and determine deficiency changes over time (e.g. crack growth) or overlay them and check for deformations. The software and scan model is also a great visualisation tool to present the state of the infrastructure to their owners (see Figure 4).

Data mapping takes place in interactive digital mapping software. The software offers the ability to display the full coloured digital tunnel model with a real-time cross-section display and dimensions at various locations including statistical values such as volume. The final generated digital tunnel model is imported into the software for data manipulation and analysis in a 2D mode. The 2D viewer mode unfolds the tunnel image and displays it on a plane with an orthogonal viewing point. This allows for easier data analysis. Data reduction can be performed to filter or mask distorted and excessive data to ensure a quality digital tunnel model for further inspection and mapping.

The goal of a tunnel scanning survey is to be able to observe the tunnel surface, detect visible defects and record it using digital mapping tools. Tunnel Information System (TIS) is a tool that allows mapping of deficiencies such as cracks, spalls, or moisture. TIS provides a flexible object database that enables a 3D localisation of objects within the tunnel. All mapped objects can be assigned with the respective inspection terminology key. Each defect was stored into the database



### References

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 Wimsatt et al. *Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings*. (The Strategic Highway Research Program 2, Transportation Research Board of the National Academies, December 2012)

Left: Figure 5, Categorising of deficiencies

### CONCLUSIONS

As engineers, we should always strive to use the latest and most efficient technologies for our clients who are tasking us to rehabilitate or inspect a piece of infrastructure that is likely severely overdue as demonstrated by ASCE's overall infrastructure rating of a D+. Every category that states the needed expenditures but one in ASCE's report outlines expenditures in the billions, with drinking water over a trillion. These numbers are overwhelming to say the least, but if we do nothing, our nation will begin to digress in quality of life and economic impacts will be felt. In fact, ASCE states that if nothing is done, disposable income will be impacted USD 3,100 a year for each American family.

Each of the inspection technologies discussed meet all of the key aspects new inspection technologies need to provide in order to gain the interest of infrastructure owners and the engineers implementing the inspections so badly needed.

The current standard of sending in large teams of inspectors that rely on the accuracy of the human eye often in miserable conditions is slow, costly, and does not provide all of the digitized and quantitative data provided by the methods discussed. The drawback of using these technologies is that their use in tunnel inspections are in their infancy and therefore are foreign to most owners and tunnel professionals, but with exposure to the benefits of these technologies it is hoped that the methods discussed above become the norm.

With the technologies discussed, efficient and in-depth infrastructure inspections can be performed efficiently and cost effective to begin to thoroughly analyse and document the state of critical pieces of infrastructure so that repair and upgrade schemes can be developed and implemented.

Our current approach of 'fix it later' is not working and is putting our society on the edge of economic disaster that once felt, is likely insurmountable

including an identification number, dimension, description, and location (see Figure 5).

For crack detection, the TIS module has a semi-automated crack detection function for precise localisation and dimensions. Initiated by user-given estimations of crack start and end points, the software initiates an automated crack tracing on the basis of local line fitting and mathematical observations in both directions of the crack. Several restrictions, rules and optimisation criteria to find the correct crack trajectory are taken into account. The crack tracing process creates polygons of the extracted cracks and feeds them into TIS. This method is applicable to various types of surface texture.

### TUNNEL MAPS

Tunnel maps are common types of reports to portray the existing condition of the tunnel lining. Tunnel maps can be generated from the scan model illustrating the rendered point cloud with the tunnel invert, sidewalls and crown 'folded out' to enable representation of the tunnel perimeter in a flat map, on which all documented features (e.g. deficiencies, joints) are recorded with respect to both their longitudinal and radial position.

### FUTURE TUNNEL SCANS

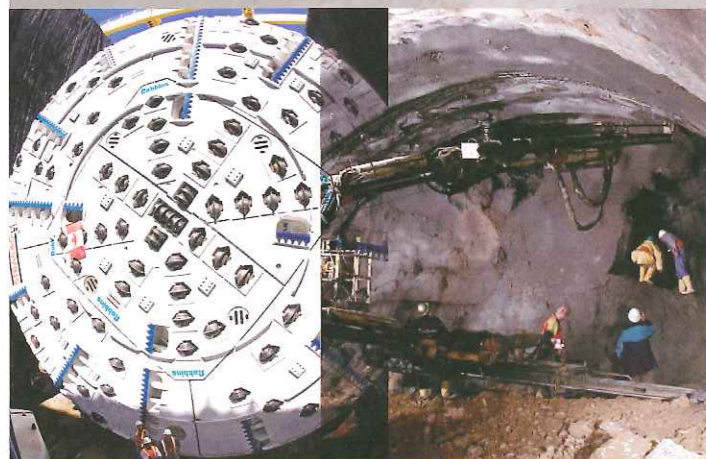
The result from a tunnel scan is a comprehensive digital representation of the tunnel in its existing condition. The data obtained through the scanning system reflects the state of the tunnel in a modern and very detailed way. The true colour rendered scan model can be visualized on current computers with very powerful software and a variety of results can be derived from it.

What makes this hybrid scanning technology stand out from other terrestrial laser scanners is the integration of high-resolution imagery, which enhances the quality of the scan model to a point, which makes it efficient for investigating tunnel lining surfaces. It is also a great tool for monitoring deficiencies over time.

As soon as a baseline scan is done, follow up scan data can be compared against each other to determine timely changes.

This technology has been used in conjunction with tunnel condition assessments in Europe for the past 10 years and its use continues to grow there on rail, subway, road, and water tunnels. Examples of recent tunnel scanning for US projects includes the Boston, San Francisco and St Louis subway tunnels.

All technologies presented in this paper are products of Dibat Measuring Technique USA (DMT). Other companies that produce similar products and solutions are: Spacetec, Datengewinnung, Amberg Technologies, and Geodata Group.



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- Edmonton Southeast and West LRT
- Los Angeles SR 710 Gap Closure Tunnel
- Gotthard Base Tunnel (57 km)
- Brenner Base Tunnel (56 km)

# WRAPPING FARRINGDON

Angelos Gakis was a runner-up for this year's Harding Prize. This article is based on his paper, 'Design of a SCL wraparound tunnel utilising a 3D geological model at Crossrail's Farringdon Station'. The

**L**OCATED IN the heart of Crossrail, Farringdon will become one of London's major rail interchange stations, providing connection between three networks (Thameslink, Crossrail and London Underground). The station also has a distinguished role during the construction of Crossrail project, as it is intended to receive four earth pressure balanced tunnel boring machines (TBMs): the two Drive X TBMs, running from Royal Oak to Farringdon and the two Drive Y TBMs, running from Limmo to Farringdon.

The complete station layout will comprise two ticket halls, two platform tunnels (Eastbound - PTE and Westbound - PTW), connecting cross passages, escape and ventilation adits, two escalator inclines and two concourse tunnels that will be mainly constructed using sprayed concrete lining (SCL) tunnelling. This open face, sequential tunnelling method was preferred due to the flexibility that it provides with regards to the tunnel size and geometry. In total, approximately 1000 linear metres of SCL tunnels with cross sectional area varying from 25m<sup>2</sup> to 110 m<sup>2</sup> will be constructed at axis depths of approximately 30m below ground level. The majority of the tunnelling will take place within the Lambeth Group formations.

Crossrail awarded the contract to BAM Nuttall, Ferrovial Agroman and Kier (BFK) Joint Venture in 2011 that appointed Dr. Sauer & Partners (DSP) as specialist consultant on the SCL tunnelling works, providing lining design and ground support design prior to ring closure. The Employer's SCL designer (Mott MacDonald) was responsible for the permanent works design including the composite SCL tunnel linings post-ring closure.

### TUNNELLING WORKS PROGRESS

The 10.5m high by 11.5m wide platform tunnels in Farringdon station will be enlarged from the TBM pilot tunnels (6.2m radius - 7.1m considered for the cutter head) using SCL techniques. The western part of Farringdon station shown in Figure 1, comprises the lower concourse tunnel CH1 and the escalator tunnel ES1, cross passages CP1, CP2 (a&tb) and CP3 (a&tb), a ventilation adit (VA1), stub tunnels STW1, STW2 and STW3, platform extension tunnels PL1 and PL2, temporary connection adit CP1-CH1 and PL2RC wraparound. Access to the SCL works was provided through shafts SH-W1 and SH-W2.

Originally, the construction of the cross passage CP1 (7.2m high by 6.3m wide) was planned to finish with a temporary headwall (Figure 3), approximately 5m before the intersection with PTW, with a subsequent pause until the enlargement of

### Angelos Gakis

Angelos is a senior tunnel engineer with Dr. Sauer & Partners, based in London, UK



PTW would take place, when the two tunnels would be connected.

According to the construction programme, shaft SH-W1 had to be backfilled with foam concrete prior to the arrival of the eastbound Drive X TBM (3/12/2013), hence, no SCL works through this shaft could take place between November 2013 and March 2014. Additionally, due to logistic reasons, lowering equipment for the probing works in the westbound platform tunnel (PTW) through shaft SH-W2 would not be possible. This potential delay called for a versatile solution that had to be designed and approved within a narrow time frame.

### THE ROLE OF PL2RC WRAPAROUND

The 8.85m high by 8.0m wide PL2RC wraparound was envisaged as an effective solution with regards to the aforementioned delays, providing rapid access to the TBM tunnel and allowing probing and subsequent enlargement works for PTW to commence shortly after the westbound, Drive X TBM transit. In addition, the SCL works for the enlargement of CH1 tunnel would be able to resume directly after the establishment of the connection between CP1 and PTW through PL2RC.

The tunnel was constructed at a depth of approximately 30m below ground level using open face excavation. A 350mm thick steel fibre reinforced, concrete primary lining was sprayed without any additional reinforcement or SCL thickening. Apart from the time

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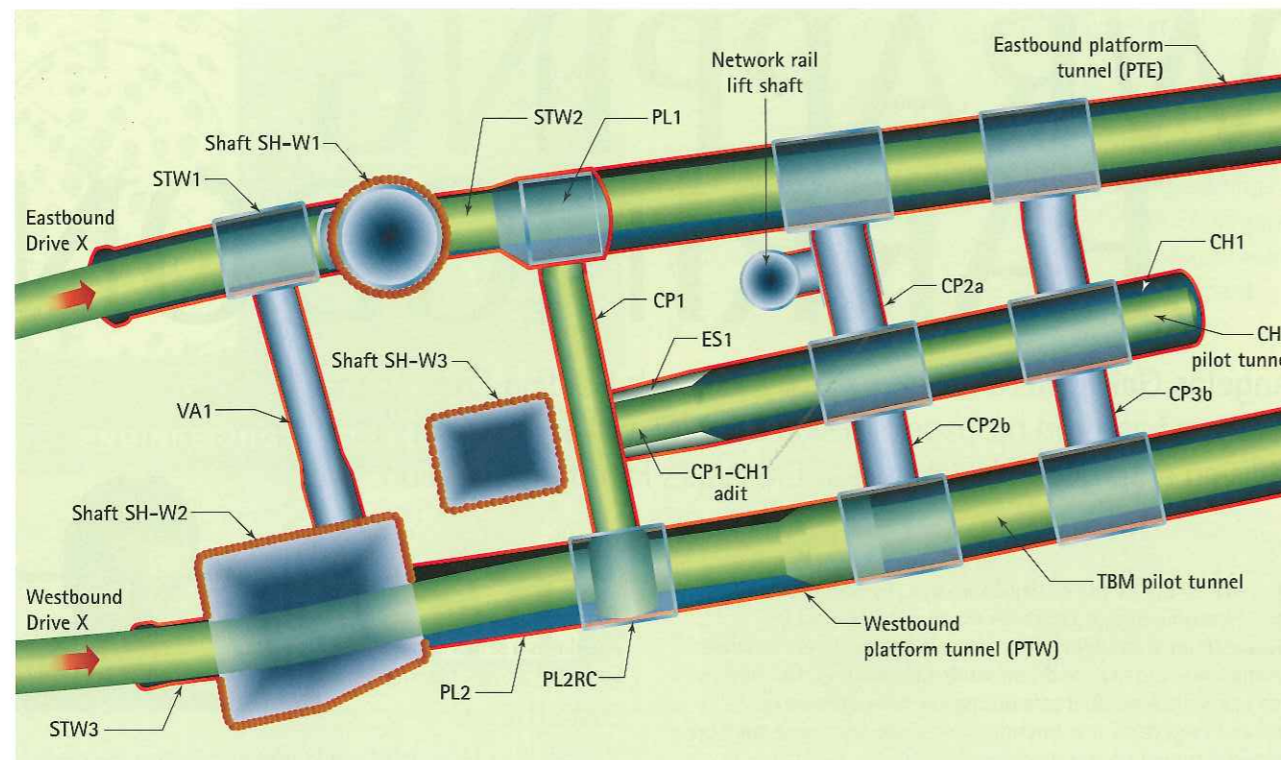
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and cost saving, an important Health & Safety benefit from the exclusion of steel bar reinforcement was that no working at height for its installation was required. The geometry of PL2RC is represented in Figure 2. The construction steps related to the construction of PL2RC were the following:

1. Extension of CP1 by approximately additional 5m from a temporary headwall.
2. Construction of the transition from CP1 (area 36 m<sup>2</sup>) to PL2RC (area 57 m<sup>2</sup>) excavated in top heading, bench, invert steps with a 350mm thick steel fibre reinforced primary SCL.
3. Construction of PL2RC excavated in top heading, bench, invert steps with a 350mm thick steel fibre reinforced primary SCL (Figure 3, left-hand side).
4. Back-filling PL2RC with foam concrete for the passage of the westbound TBM.
5. Passage of westbound TBM pilot tunnel through PL2RC.
6. Establishment of connection between CP1 and westbound TBM by partial removal of the foam concrete back-fill and the TBM segments (Figure 3, right-hand side).
7. Back-filling shaft SH-W1 with foam concrete for the passage of the eastbound TBM.
8. Excavation of CH1 Enlargement and concurrent probing works in the westbound TBM tunnel for the forthcoming PTW enlargement.

Above: Figure 1, Plan view of the tunnel structures in the western part of Farringdon Station. The completed tunnels in December 2013 are shown in green. Principal access for the SCL works was via shafts SH-W1 and SH-W2

The 31 steps of top heading, bench and invert excavation were completed within 14 days (1/8/2014 to 15/8/2014), exhibiting an average advance rate of 1.2 m/day.

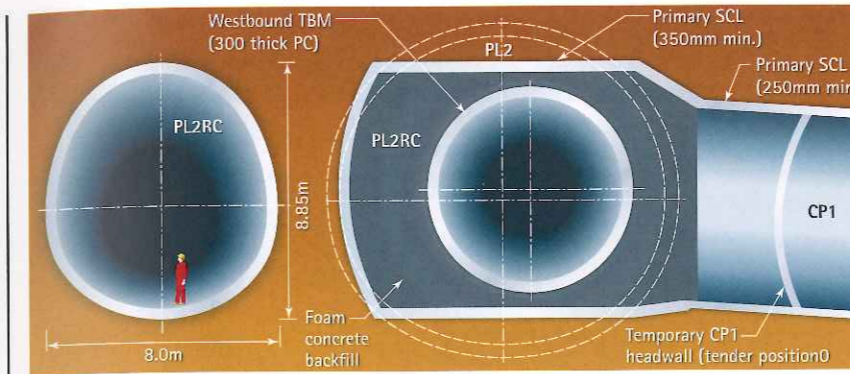
### GEOTECHNICAL DESCRIPTION OF THE FARRINGTON STATION AREA

The geological formations in the area of Farringdon Station are the typical of London basin, with the upper strata comprising Made Ground and River Terrace Deposits overlying London Clay, the Lambeth Group Formations, Thanet Sand and the Chalk bedrock.

The following key aspects of the geology of Farringdon were considered in relation to the tunnelling works:

- Unlike the majority of the SCL tunnelling works in London, the tunnels in Farringdon would be predominantly constructed in the Lambeth Group formations (some 83 per cent of the tunnelling works), comprising stiff to very stiff over-consolidated clays with randomly distributed sandy units of variable size, continuity and pore water pressure regime.
- The presence of multiple faults inside the footprint of the station affecting the thickness, the elevation and the continuity of the soil layers.
- The thickness of the London Clay unit varied between 4m and 22m due to the geological faulting and the presence of the buried valley of the Fleet River in the area of the West Ticket Hall.
- Due to the historical water abstraction, the deep aquifer (Upnor Formation, Thanet Sand and Chalk) induced an under-drained pore water pressure effect to the overlying formations.

This geological complexity and variability in combination with the scarcity of borehole information above the alignment of PL2RC, due to the presence of the Network Rail tracks and sidings, called for a sophisticated investigation and geotechnical risk management strategy.



### DEALING WITH GEOTECHNICAL RISK

An optimised geotechnical risk management framework was integrated in the site supervision workflow, exploiting all the available information, aiming to ensure excavation stability, rapid ring closure and minimal surface settlements as required for the protection of the existing assets. This has required the presence of competent supervisory staff in the key roles of the "Senior SCL Engineer" and "Chief Geotechnical Engineer". The assembly of all the data and the excavation and support management was embedded into the Shift Review Group (SRG) and Required Excavation and Support (RES) processes, enabling the highest possible standards of geotechnical risk management to be delivered to the project.

Three main tools were deployed in order to collect and process geotechnical data and integrate it into the cycle of risk reduction (Figure 4): in-tunnel probing (prescribed throughout the SCL works), data acquired from the tunnel excavation producing face mapping records and the 3D geological model that was updated on a daily basis allowing for geological predictions of increasing accuracy to be made.

#### In-tunnel probing

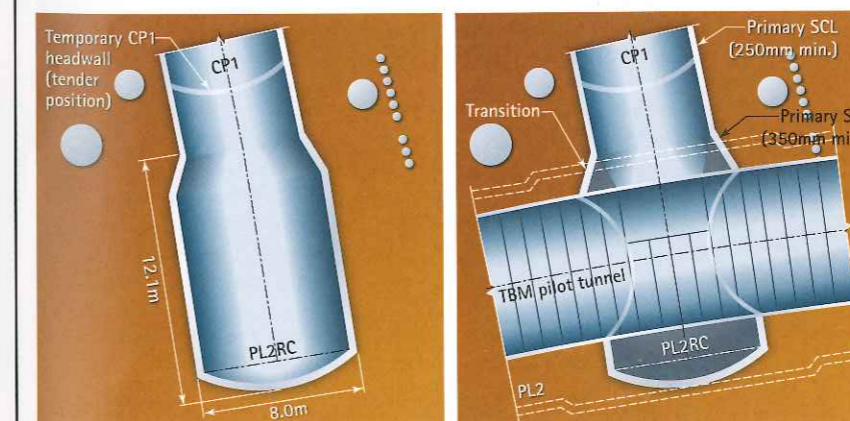
Optimised probing patterns ahead of the excavation face were prescribed for all the SCL works utilising dry auger drilling through a rig-mounted blow-out preventer, in order to identify potential water charged sand units that might induce instabilities during the tunnelling works.

The implementation strategy was differentiated for tunnels that would be constructed following a "top heading - bench - invert" excavation and tunnels that would be constructed following a "Pilot - Enlargement" excavation:

- The investigation for the tunnels that would be constructed following a "top heading - bench - invert" excavation, such as PL2RC, was performed ahead of the tunnel excavation, by drilling inclined and horizontal probe holes from the

Above: Figure 2, Details from PL2RC construction drawings, showing the cross section (left) and the longitudinal section (right).

Below: Figure 3, Plan view from PL2RC construction drawings, showing the initial stage after the completion of the construction of PL2RC (Left) and the final stage, after the passage of the westbound TBM, the partial removal of foam concrete and the break in to TBM Pilot tunnel to create access for PTW/PL2 Enlargement works (Right).



sealed excavation face, typically covering minimum 12m of excavation with an overlap of 3m between successive arrays.

- The investigation for the advancing enlargements of tunnels constructed following a "Pilot - Enlargement" excavation, such as platform tunnel west, was performed by drilling radial probe holes within the previously installed pilot tunnels. The requirement of investigating minimum 3m around the outline of all the enlargements was established for all these tunnels.

All the investigation drilling was logged by a geotechnical engineer and the results were presented in longitudinal and cross sections. Two inclined probing arrays consisting of 9 probe holes, 12m long each, were designed and drilled for PL2RC.

A flow chart was developed to assist the future determination of actions based upon the probing results, which including criteria for water flow and pore-pressure control. The steps prescribed in this flow chart were followed successfully during recent encounters of water bearing Sand Lenses while probe drilling for the enlargement of PTW was carried out.

#### Face Mapping

The open face excavation using sprayed concrete linings provides the opportunity for detailed geological observations to be made and documented through the face mapping process.

The geological conditions in every single excavation step were being recorded and classified according to BS 5930:1999, providing a large scale ground investigation in a horizontal direction.

The encountered geology was in excellent match with the in-tunnel probing results and validated what both in-tunnel probing and 3D geological model had already predicted; that the Farringdon Fault would not be encountered during the excavation of PL2RC.

#### 3D Geological Model

The 3D geological model for the area of Farringdon station was first developed in 2009 by the British Geological Survey (BGS) [see Aldiss et al 2012], using data from historical boreholes and site investigation carried out for Crossrail. Due to the complexity of the geology of the station, BFK/DSP proposed to develop the model and to use it as an integral part of the site supervision

workflow and provide a tool for three-dimensional illustration of the geological units and a basis for predictions for the excavation of tunnels.

Initially, the additional data from borehole drilling and excavation of shafts that was received between 2009 and 2013, were digitised and incorporated in the model by the author, resulting in a significantly updated version. Some 58 additional boreholes were implemented in the 2013 update.

Even more significant, was the update of the model that was performed on a daily basis, making use of the continuous data derived from face mapping and probing, increasing the accuracy of the model and allowing for predictions of increasing reliability with time for future excavations.

The first prediction in Farringdon Station was performed for tunnels STW2 and PL1. At that point in time, face mapping data had not been yet used to update the model.

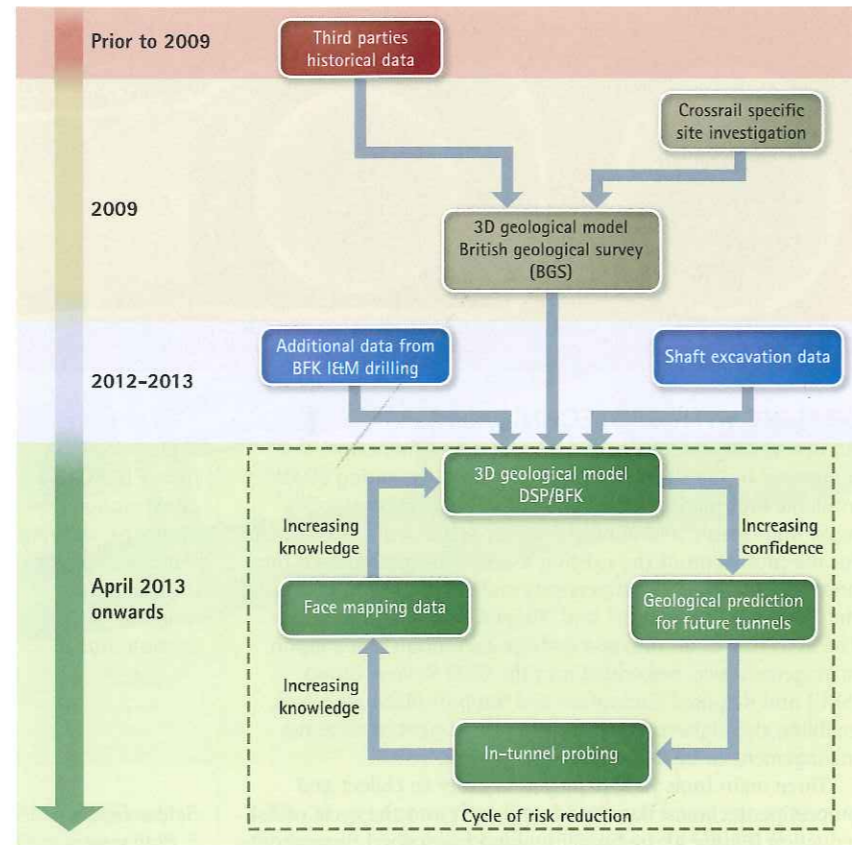
A prediction for PL2RC was also performed, providing a significantly improved match to the actual stratigraphy. In the area of CP1 and PL2RC very little borehole data was available, however, the data from the excavation of STW2-PL1 that was integrated in the 3D model proved sufficient to increase the accuracy of the prediction.

**Geotechnical risk mapping**

A mapping of the risk related to water charged sand units that could affect the SCL tunnelling works in Farringdon, was performed by the author. One map was for the design phase, referring to April 2012 when only preliminary geotechnical investigation data became available whereas mapping of the construction phase in June 2013, had a three dimensional (3D) finite element (FE) model for PL2RC in progress with additional data from ground investigation becoming available as a by-product of 25 boreholes drilled for the installation of the instrumentation and monitoring devices and the excavation of STW2-PL1. This data was used to update the 3D geological model, providing an updated mapping of the geotechnical risk.

The assumptions used for the risk mapping are listed below:

- Grade V [red] applied to either "low confidence" in the knowledge of the geological environment and/or evidence of water bearing sandy units in the tunnel horizon.



Above: Figure 4, Cycle of risk reduction through the implementation of geotechnical risk management tools (Gakis, Salak, StJohn 2013)

- Grade I [blue] applied to parts of the station that had already been excavated or thoroughly investigated, thus providing a high level of confidence.
- The risk was higher for large tunnels and tunnels that would be intersected by faults.
- The area east of Smithfield Fault was assigned an increased risk by default, as the pore water pressure regime was higher and tunnels were excavated within more risk-prone geological formations (the Upper Mottled Beds).
- Equally effective in-tunnel investigation (probing) would be carried out for all the structures, reducing the risk by the same amount.

The effective reduction of risk in PL2RC from Grade III in the "design phase" to Grade II in the "construction phase" was due to the updated predictions from the 3D geological model that suggested that neither Farringdon Fault nor Sand Lenses would be encountered during the excavation.

**THREE DIMENSIONAL FINITE ELEMENT MODEL**

A sophisticated non-linear 3D FE analysis was carried out by the author using ABAQUS Version 6.12 released 2011 (Dassault Systemes Simulia Company), in order to assess the capacity of the primary sprayed concrete linings (SCL), and openings of PL2RC during its construction and after the passage of the westbound TBM respectively.

The sequential excavation and lining installation were modelled using a multi-step analysis following the designed excavation and support sequences. Figure 5 provides a perspective view of the structures that comprised the 3D FE model.

Data provided by the latest update of the 3D geological model was used to simulate the anticipated geology, assuming that Farringdon Fault would not be encountered during PL2RC excavation.

Table 1. Soil Parameters used in the FE models. Drained parameters were used for the Upper Strata and the Thanet Sand units, and drained parameters were used for the London Clay and the Lambeth Group units. Z denotes the distance from the top of the London Clay layer.

Soil Properties		Upper Strata	London Clay	Lambeth Group	Thanet Sand
Unit Weight	[kN/m <sup>3</sup> ]	17	20	21	21
Young's Modulus	[MPa]	10	40+3.7z	36+5.9z	209+4.3z
Poisson's Ratio	[-]	0.2	0.495	0.495	0.2
Undrained Shear Strength	[kPa]	N/A	85+6.5z	95+10z	N/A
Friction Angle	[o]	31	0	0	39
ko	[-]	0.5	1.2/0.6	1.2/0.6	1.0

Source: Author

Table 2. Steel fibre reinforced concrete (SFRC) SCL parameters used in the FE models.

Parameter	Value
Characteristic cylindrical compressive strength of SFRC	28 MPa
Characteristic residual tensile strength for SFRC	0.45 MPa
Elastic Modulus (Primary Lining only)	13 GPa
Poisson's ratio	0.2

Source: Author

**Design Considerations**

Approximately 130,000 linear tetrahedral solid elements were used to simulate the soil units and 9,800 linear triangular shell elements to simulate the steel fibre reinforced SCL primary lining in 46 steps of analysis.

The soil materials were modelled using the elastic-perfectly plastic Mohr-Coulomb model, taking into account the variation of stiffness with the strain level, assuming a higher strain level in the proximity of the tunnel excavation and a lower level for the remaining areas following the results of preliminary 2D FE calibration analyses performed using Phase2 finite elements package (RocScience). In addition, depth-dependent strength and stiffness parameters of the soil materials were assumed. These considerations allowed the model to capture the basic features of the more advanced constitutive models.

Two values for the at rest earth pressure coefficient were

Below: Exposed top heading of PL2RC, presenting units of the Lambeth Group: Upper Mottled Beds (Clay); Laminated Beds (Silty Clay-Silt); Lower Shelly Beds (Clay); Mid Lambeth Group Hiatus; Lower Mottled Beds (Clay and Sandy Clay)



used in two models, ko=1.2 and ko=0.6. The first exhibited the highest lining stresses and was therefore used in the lining capacity checks, whereas the latter produced more realistic results in terms of in-tunnel and surface deformations and was used for the deformation predictions (similar conclusions are presented in the research performed by Gakis, Flynn, Nasekhian in 2013).

The analysis was performed assuming undrained conditions, due to the "fast" construction in comparison to the time required for consolidation of the stiff overconsolidated clays. Moreover, no groundwater pressure was applied on the SCL lining as it was considered to be permeable in the short term (prior to the installation of waterproofing layers). The soil parameters used in the FE models are listed in Table 1.

For the steel fibre reinforced SCL, the elastic-plastic "concrete damaged plasticity model" was used (Dassault Systemes Simulia 2011). The behaviour of the material was simulated as ideally elastic prior to compressive and tensile yield. The 28-days compressive strength and the residual tensile strength parameters were considered in the post-yield states. The elastic modulus for the primary lining accounted for the time dependent hardening of the steel fibre reinforced SCL (see John & Mattle 2003 and Poettler 1990). The parameters used in the FE models are listed in Table 2.

The parameters for both soil and the steel fibre reinforced SCL, were taken in accordance with the Design Statement for Temporary SCL Works (Crossrail C435 2013).

**Primary lining capacity**

The capacity of the SCL was checked by means of capacity limit curves (Sauer et al 1994) using the design methodology for sections under axial load and bending from the RILEM (RILEM 2003). Lining sections and structural

members were checked in accordance with the Crossrail Civil Engineering Design Standards. The effect of the compensation grouting that was applied approximately 5m above the crown of the wraparound, as a mitigation measure against the induced settlements, was considered as a separate load case. The assumed area of application of the grouting pressures was divided in four panels and the pressure was applied individually on each panel and simultaneously on all panels.

### Surface and in-tunnel deformation results

The Network Rail sidings, located above the alignment of CP1 and PL2RC was the main asset that had to be protected. The deformation results were extracted from the model using  $k_0=0.6$ . Surface monitoring results above PL2RC were only available from the readings on the Network Rail sidings, hence, the comparison had to follow this alignment. It is evident that the 3D FE model prediction produced a very close match with the observed settlements, slightly overestimating the absolute magnitude. A reasonable explanation would be that the stiffness of the sidings induced a "bridging effect", resulting to the targets that were positioned on them monitoring a slightly different settlement trough than the actual ground surface.

For the comparison of the in-tunnel deformations, the results obtained from the monitoring arrays that were installed in PL2RC at TM 34.400 and TM 38.300 were used. The prediction of the 3D FE model was in good agreement with the observed in-tunnel deformation.

### CONCLUSIONS

The PL2RC was constructed deploying a 350mm thick steel fibre reinforced SCL primary lining without any additional reinforcement or thickening, optimising significantly the programme in Farringdon Station. An innovative design was carried out by combining a sophisticated non-linear 3D FE model that simulated accurately the steps of the sequential excavation and the geometry of the tunnel, with the 3D geological model, integrating the most recently acquired geological data.

The design check for the primary lining capacity was based on the results from the 3D FE model with  $k_0=1.2$  using capacity limit curves. The predicted in-tunnel deformations, and surface settlements due to construction of PL2RC using a 3D FE model with  $k_0=0.6$ , showed a very good match with actual monitoring results

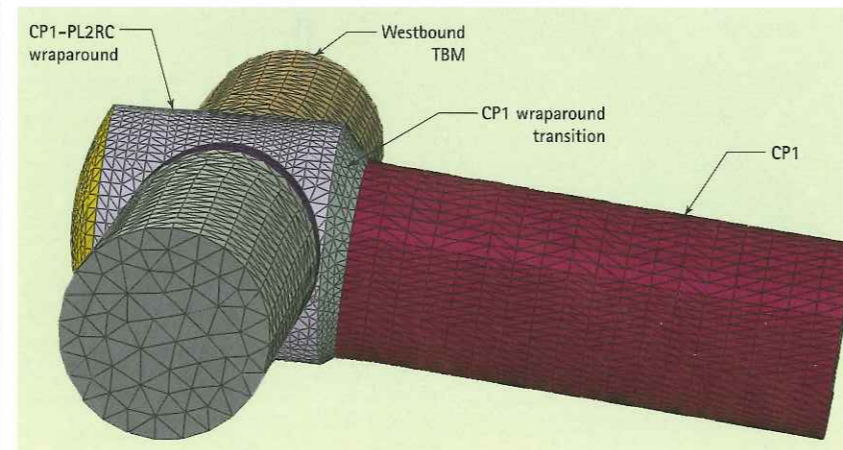
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**Editor's note:** The original paper was exceptionally well illustrated, with in excess of 25 diagrams produced by the author. Regrettably only a select few could be reproduced with this article. Recognising that this will dilute the result, we highly recommend the reader also views the original paper, which can be found on the BTS website's events section, under the Harding Prize tab: [www.britishtunnelling.org.uk](http://www.britishtunnelling.org.uk)

Below: Figure 5, Perspective view of structures included in the 3D FE model



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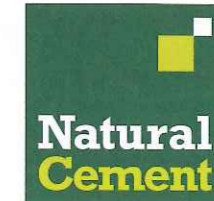
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27 January 2015  
New York, New York  
In recognition of his accomplishments, the UCA of SME holds this annual one-day conference.  
[www.smenet.org](http://www.smenet.org)

**Shotcrete conference and exhibition**  
29-30 January 2015  
Tyrol, Austria  
Wolfgang Kusterle and his team welcome you to the Conference and Exhibition Shotcrete 2015 at the Alpbach Conference Centre. Knowledge and experience do not help, if they remain hidden. This platform has gathered shotcrete specialists for 25 years.  
[www.spritzbeton-tagung.com](http://www.spritzbeton-tagung.com)

**ICETUS 2015**  
3-5 March 2015  
Subang Jaya, Malaysia  
Following the successful International Tunnelling and Trenchless Technology Conferences held in Malaysia in 2006 and 2011, the Tunnelling and Underground Space Technical Division of The Institution of Engineers, Malaysia, is holding its third conference to coincide with KVMRT developments.  
[www.icetus2015.iemtc.com](http://www.icetus2015.iemtc.com)

**ISRM Congress 2015**  
10-13 May 2015  
Montreal, Canada  
Held in conjunction with the CIM Convention for 2015, the International Symposium on Rock Mechanics is an international conference every four years. A one-day symposium on "Shale and Rock Mechanics" is planned.  
[www.ISRM2015.com](http://www.ISRM2015.com)

**World Tunnel Congress 2015**  
22-28 May 2015  
Dubrovnik, Croatia  
WTC 2015 heads to the Dalmatian Coast as the event returns to Europe. Further details to be confirmed.  
[www.wtc15.com](http://www.wtc15.com)

**RETc**  
7-10 June 2015  
New Orleans, Louisiana  
The Underground Construction

Association's biennial conference.  
[www.smenet.org](http://www.smenet.org)

**49th US Rock Mechanics / Geomechanics Symposium**  
28 June-1 July 2015  
San Francisco, California  
The 2015 program will focus on new and exciting advances in rock mechanics and geomechanics and encompasses all aspects of rock mechanics, rock engineering, and geomechanics. Field trips and technical tours are planned.  
[www.armasymposium.org/](http://www.armasymposium.org/)

**Eurock 2015 & 64th Geomechanics Colloquium**  
7-10 October 2015  
Salzburg, Austria  
The Austrian Society for Geomechanics has the pleasure to invite you to the ISRM Regional Symposium EUROCK 2015 Future Development of Rock Mechanics, to be held in conjunction with the 64th Geomechanics Colloquium in Salzburg.  
[www.eurock2015.com](http://www.eurock2015.com)

**25th World Road Congress**  
2-6 November 2015  
Seoul, South Korea  
The World Road Congress has been held every four years for more than 100 years. Since the first meeting in Paris in 1908, it has toured the member countries of the non-government organization, Permanent International Association of Road Congresses (PIARC).  
[www.aiperseoul2015.org](http://www.aiperseoul2015.org)

**RETc**  
14-18 March 2015  
Sendai, Japan  
UNISDR is facilitating the process of developing a post-2015 framework for disaster risk reduction. This process will culminate at the 3rd United Nations World Conference on DRR  
[unisdr.org/ue/coordinate/hfa-post2015](http://unisdr.org/ue/coordinate/hfa-post2015)

**Stuva Conference**  
1-3 December 2015  
Dortmund, Germany  
Held every two years, this conference sees 1,500 participants and visitors from about 20 countries. It is numbered among the world's leading get-togethers for underground construction experts.  
[www.stuva-conference.com](http://www.stuva-conference.com)

2016

**World Tunnel Congress 2016**  
22-28 April 2016  
San Francisco, USA  
WTC 2016 heads to the Golden State as the event heads to North America. Further details are to be confirmed.  
[www.wtc2016.us](http://www.wtc2016.us)

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The BTS has a membership of almost 700 individual and 60 corporate members. It is one of the most vibrant gatherings of professional tunnellers in the world and traces its history back to its founding in 1971. Regular BTS monthly meetings are hosted at the Institution of Civil Engineers in London from 5.30pm every third Thursday of the month. In recent years, the BTS Young Members have also begun hosting a programme of evening lectures.

**Removal of foreseen and unforeseen underground obstructions on MTRC Express Rail Link no. 820, Hong Kong**  
20 November 2014

In October 2010 Dragages/Bouygues TP were awarded the GBP 315M contract to build the section of the high-speed rail link between Hong Kong and Guangdong. The structure consists of two parallel single-track tunnels each 3.5km long and linked by 14 cross passages. The 9m internal diameter tubes were constructed using two slurry TBMs. This presentation will address one of the biggest difficulties that had to be overcome on this project. The speakers are Vincent Avrillon of Bouygues and James Musgrave, ARUP.

**Debate - This house believes that Regulation and the accompanying Compliance culture is stifling Innovation and Creativity within the tunnelling industry**  
11 December 2014

This year's traditional pre-Christmas debate looks into innovation within our industry and the factors which promote or stifle it. Speakers include Bob Ibell, London Bridge Associates, and Bob Cummins, Hollins Consulting, (For); and Kevin McManus, London Bridge Associates, (Against);

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