

WORLD METROS SUPPLEMENT

# Tunnels



AND TUNNELLING



WORLD METROS

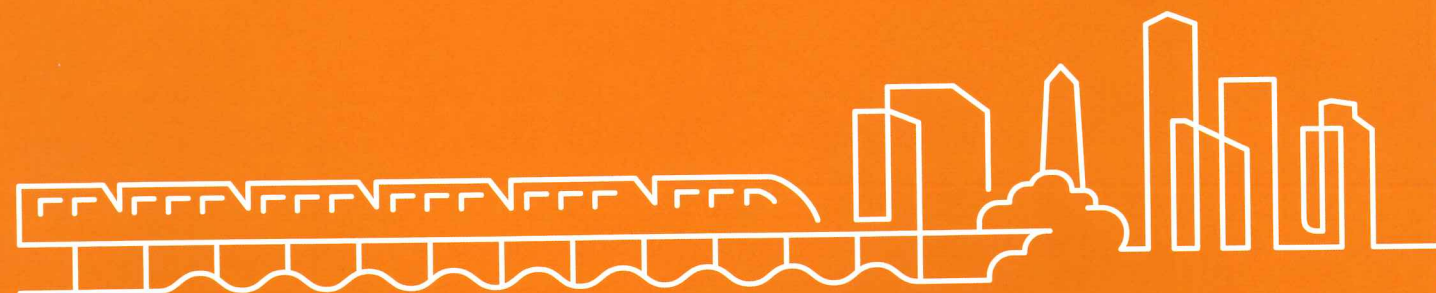
*A guide to underground transport*

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## FLAGSHIP PROJECTS

**M**ETRO PROJECTS are without a doubt the flagship of the tunnelling industry. Sewer, water, and more recently telecommunications projects may provide a bulk of the work over time, but when the public think of tunnelling, they think of urban train networks. In a recent interview with Tunnels and Tunnelling, past president of the International Tunnelling Association Martin Knights identified London as the sustained capital of tunnelling outside of East Asia.

While it cannot compete with China as a whole, for example, Knights pointed to the marriage of clients aware of the benefits of going underground, with private businesses aware of the part they play, in bringing a truly world-beating level of investment in underground infrastructure to the capital of the United Kingdom.

Tunnels and Tunnelling has also been made aware that potential clients and other stakeholders are being encouraged to attend the upcoming World Tunnel Congress in San Francisco.

There seems to be a new focus by the industry on engaging with all potential stakeholders that may be affected by, or hold some influence of the successful realisation of a tunnelling project.

This supplement gives a summary of just some of the metro projects around the world that have necessitated underground solutions, and in distributing this supplement to key clients around the world, as well as to our regular leaders, the Tunnels and Tunnelling team hopes to do its part in advancing tunnelling as a solution to the challenges of an increasingly urbanised global population.

We have included brief summaries of the technological concerns that will be of interest to clients.

It is in the interest of the industry to do everything it can to promote innovative solutions to the challenges that arise from underground metro construction projects.

Tunnels and Tunnelling

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**Kevin Whalen,**  
Superintendent  
Turner Construction,  
Seattle

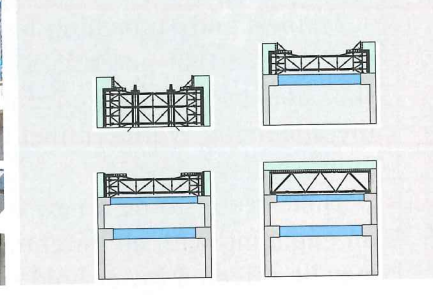
"Working in collaboration, PERI and Turner Construction designed the Traveling Mono System which has met scheduling and budgetary constraints. We've increased the level of safety for our workers as well as reduced the number of man hours required to set up traditional formwork systems. This system was specifically designed to pour concrete from the ground to the roof giving us ability to maximize our labor force and allow subcontractors to work beneath the system, all while improving on the quality of the finished product."



The formwork solution is based on system components of the VARIOKIT engineering construction kit. The traveler system for the bottom level is also used in the upper levels.



The VARIOKIT traveler system rolls from one section to the next on rails after each pour, without the formwork having to be broken down and reassembled.



The three levels of Capitol Hill Station have been poured one after another – using a clever designed traveler system that is moved on rails from one pouring section to the next.

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# NOUS AT THE NODE

Metro station designs are a complex art, and not developed in isolation.  
Report by **Patrick Reynolds**

**S**TATION DESIGN is a complex discipline, and an art, as it mulls and weaves matters of location, depth, geology alignment and construction as well as space, light, comfort, health and safety. Usually so much to achieve in quite congested urban space, usually.

Architects, structural engineers, geotechnical engineers, tunnellers and fire safety specialists work to blend their diverse skills and fuse together effective designs for each station. But each site – a station being a mere node on a larger metro line project – also must help to deliver on the main purpose of the scheme: to provide sufficient, safe, effective and, increasingly these days, profitable passenger transportation in major cities.

In terms of their structural form, though, the stations generally boil down to one of two types: boxes or ovoids. However, getting to the choice of optimum form is no minor challenge.

A further dimension to station design is their internal layout with myriad matters to consider around linkages, access and egress. A station must allow for the flow of many thousands of passengers per hour at busy times like rush hour, which is a predictable challenge; but the unpredictable must be planned for, like fires and other emergencies, and modelling undertaken to safeguard evacuation.

### CARVE-OUTS AND BOXES

In terms of tunnelling method, broadly, the ovoid is a hollowed out, or mined (blasting, mechanical, and employing sprayed concrete lining – SCL) form of underground metro station; and, box stations are generally constructed as cut and cover structures. In effect, the former employs keyhole surgery while the latter necessitates a C-section.

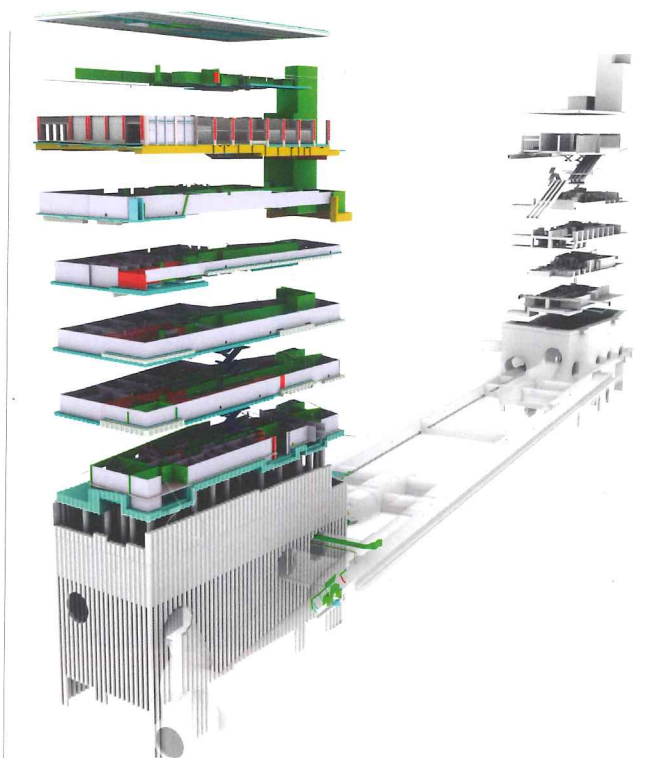
Mined caverns can be blasted deep in the hearts of congested cities founded upon strong rock, such as Hong Kong and some Scandinavian cities, or part of Rio de Janeiro; also, they can be carved as SCL chambers, being created as subterranean sculptures where ground conditions are good, like in London and elsewhere in Europe, and other international cities.

Box stations become more of an option on a metro route where the alignment runs at shallower depths, but also requires sufficient surface area to open up the ground, lower the groundwater level, and dig down between braced diaphragm and secant piled walls to bottom out with huge slabs.

Many boxes have been used in Delhi metro, for example. However, they can have deeper and narrow geometries, such as in the Cityringen metro scheme in flat, built-up historical centre of Copenhagen.

Various combinations and blends of structural types also can be developed to deal with the opportunities in some cities, and any accompanying restrictions, such as: groundwater; surrounding structures; access; proximity to other stations; and, the construction method and sequence of drives for the intervening tunnels, usually done as TBM bores.

For example, when constructing the north-south metro line in Cologne, Germany, there was limited space in the congested city to allow normal, full-size box excavation at the surface for a few stations. The solution developed was to create a slim central box – a slot, in effect – to which either side ran the bored tunnels. Then, following ground treatment and breakout from the tubes, a series of mined excavations joined the tunnels to the diaphragm walls of



Above: Multi-level station design: view of Bond Street

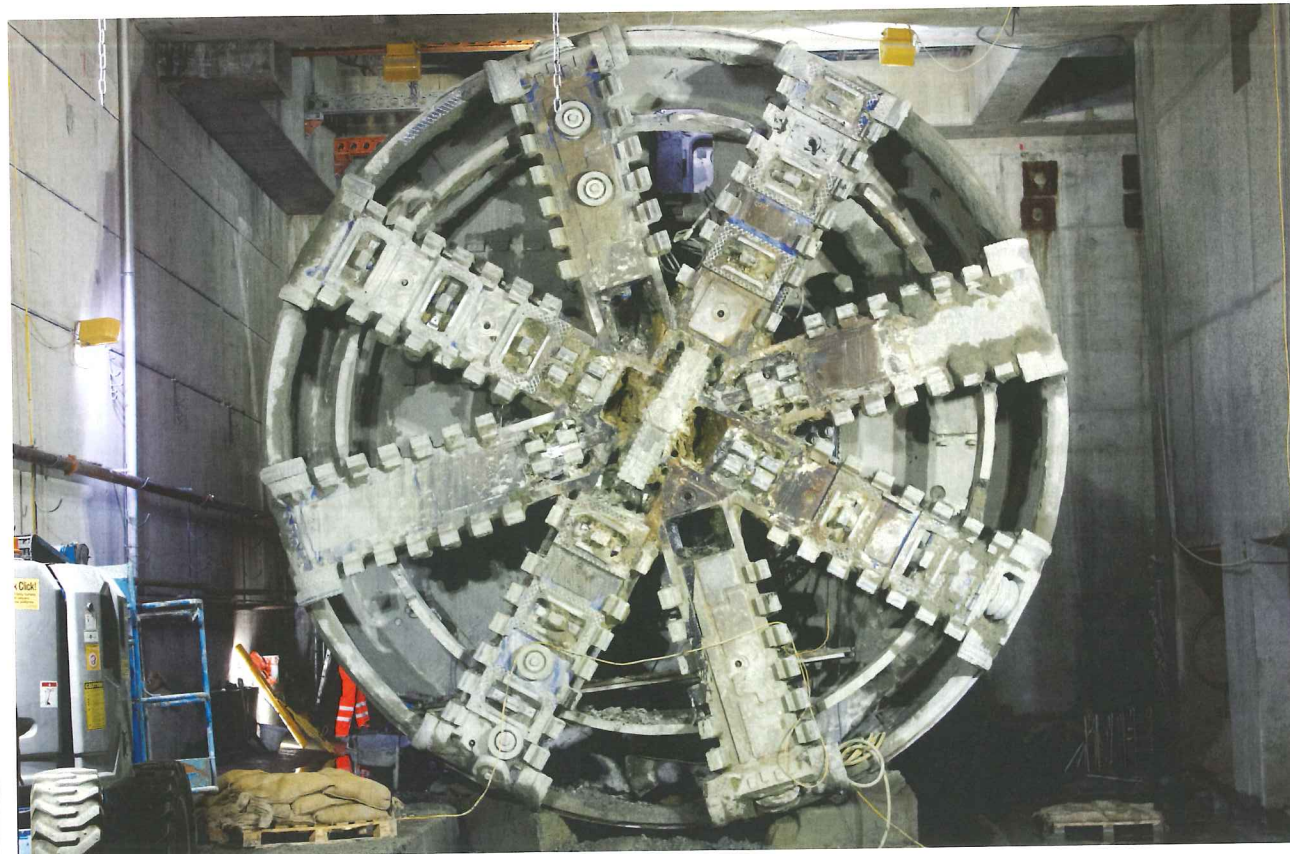
the box. These enlarged voids became full platform spaces.

There is therefore no simple, automatic or quick answer to a metro station design.

Highlighting different approaches, consultant URS describes in an about-to-be published volume (see reference box) of papers from the Institution of Civil Engineers (ICE) how two different station designs were chosen on the Crossrail scheme, in London. In the opening paper, URS discusses how quite different designs – SCL and a box – were derived for Farringdon and Paddington stations, respectively.

Farringdon has the more difficult geology of the two stations, and is the meeting point of contracts, and the termination point of tunnel bores; it is a construction and contractual interchange as well as future passenger change point. It is also located in the dense heart of central London with an existing tube station; choosing a large, open box excavation would be too difficult for the site, and so a scheme of SCL tunnelling was developed.

The SCL design and construction works developed for the station are discussed in a number of separate papers by consultant Mott MacDonald, and contractor BAM Ferrovial Kier (BFK) JV, supported by



Donaldson Associates and Dr Sauer.

Paddington is in west London, close to a tunnel portal and so where two drives would slip underground. Therefore, while relatively shallow, the choice of box structure for the station had the design and construction development influenced by the needs of the early TBM bores; the shields would hole into the station and then be pulled through for relaunch.

The system is also common with many box stations across the world, and can see TBMs make multiple short drives, phased to the needs of station build programmes.

Other discussions on Crossrail arise in the volume, including the value of common design in the architectural components for the underground stations, ensuring individual station developments needs fit with, and are supported by, an overall system; the work was done by a JV of Atkins, Grimshaw and GIA Equation.

Another feature in the increasing complexity of station and metro design and construction, and involving multiple parties, is managing data. The underground transport sector is not long in the tooth in this activity but is increasingly employing BIM for development and control, and future operational asset management should it be desired by the client.

#### PASSENGER FLOW

Passenger flow design in stations also extends to emergency evacuation.

**Above: TBM breaking into a station box**

Karl Fridolf, a fire safety researcher with SP Technical Research Institute of Sweden, stresses that designers need reliable and valid data on different parts of the evacuation system, and process, to establish total times involved.

To nail the data, Fridolf's research has involved studying evacuation from trains in tunnels (to quantify the flow rate capacity of train exits), then the evacuation of tunnels (determining walking speeds, behaviour and passenger responses). A further key aspect is establishing how these aspects of evacuation vary with time if the safe zone to be reached is not a simple, short walk away.

"A quite new problem is the introduction of very deep underground stations," says Fridolf. They found walking speed slowing as passengers climb up from depths that might measure up to 100m vertically, he adds. The challenge is coming to the fore, for example, in the expanding Stockholm metro.

"How are people both physically and psychologically affected in these circumstances?" he asks, and wonders further if it is reasonable to expect all passengers to use stairs – 'or should we look at other solutions?'

With so many variables to study, Fridolf points out that predictability is difficult. There are no universal laws, as in physics, with which to construct models, he says. Experiment is required; people need to be observed to get relevant, useful data. So, while metro systems become more technologically sophisticated with equipment and systems imported from across the world, it will be the natural differences, how the metros fit into the landscape if a city and with its people that will still demand close study – every single time, and for each project

#### References

"Crossrail Project: Infrastructure Design and Construction," Vol 1; ICE Publishing; 2015. Edited by Black, M; Dodge, C; and Lawrence, U. Foreword by Dulake, C.

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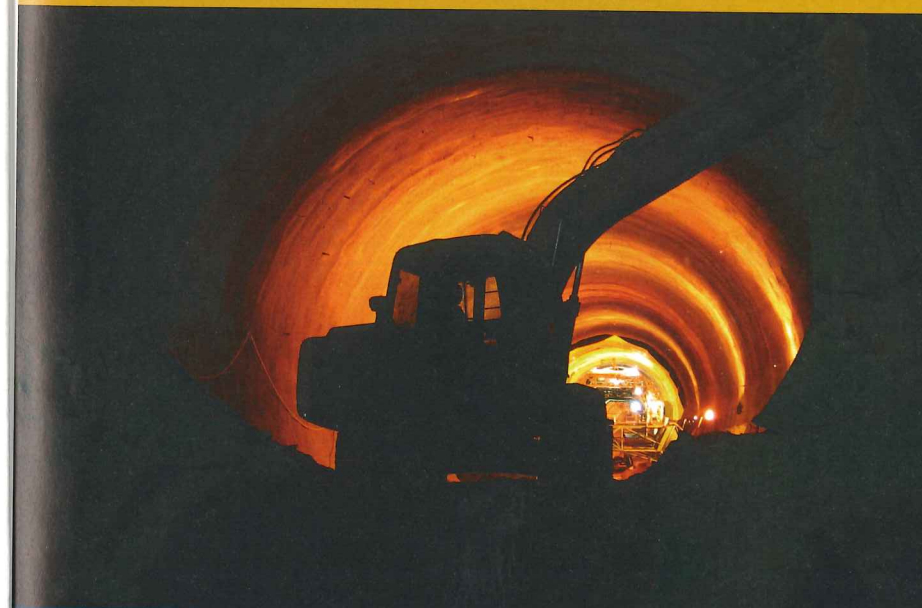
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# MAKING MOTION

New train and signalling systems are boosting transport capacities in metros.

Report by Patrick Reynolds

**O**N UNDERGROUND metros, the major civil works as well as tracks and signalling are merely background for the assets passengers usually focus on – the trains. There have been advances in all areas in recent years, and post obviously to passengers in the subway trains and signalling.

Trends in improving technology of metro trains and signalling are advancing in tandem, helping to help significantly increase the transportation capacity on the underground transit systems. Automation is a key factor, which enables more trains to safely run in the metro system and so both more journeys, and passengers carried. Or, it allows the metro system to have greater transport capacity from the same length of route; the network capacity is higher without having to build more tunnels.

Key companies that are active in trains, tracks and signalling include Alstom, GE and Siemens.

## TRAINS

Automation of rolling stock and greater energy efficiency in supporting systems are trends in metro transport systems made by manufacturers such as Alstom, GE and Siemens.

Alstom recently saw 15 of its Metropolis trains come into service on Budapest's underground transit system, on the 7.4km long Line 4 – the first automated metro line in central eastern Europe. Each train comprises five carriages. The company also supplied 22 Metropolis trains to the fleet running on Line 2 of the metro. Budapest opened its first section of metro almost 120 years ago.

More generally, and as part of the automotive sector's push for more effective preventative maintenance, another piece of Alstom equipment is HealthHub. The package has been introduced to help the clients shift from mileage-based to condition-based predicative maintenance. It can automatically scan for key consumables – such as wheels, brake pads and pantograph carbon strips – as trains pass diagnostics portals.

Siemens has Inspiro-type trains for metros, and is supplying a number to a major project in Malaysia, and recently supplied them to the Warsaw subway. For the 51km long Klang Valley Kuala Lumpur metro, in Malaysia, Siemens is supplying 58 driverless four-car trains; for Warsaw metro, the company has supplied a total of 35 six-car trains – 15 to existing Line 1 and

Below: Budapest Metro train in operation



20 to the recently built Line 2.

Features in the Inspiro design reflect key technological trends for high transport capacity, says Siemens, such as lower operating costs and greater energy efficiency. A further trend is to be more environmental friendly at every stage of development and use, including a high rate of recyclability (certified at 94.5 per cent on Oslo metro), it adds.

The basic vehicle in the Inspiro range is a six-car carriage, and trains can comprise three to eight carriages. Interior features and seat configuration as well as motorisation can be tailored to suit project needs. Weight is reduced through use of aluminium car structure and weight-optimised chassis, lessening energy demand – which also benefits from the new demand-controlled air conditioning system.

## SIGNALLING

Advances in signalling supports automatic operation of trains, which allows more and faster train movements to be coordinated, and shorter journey times. Overall, the transport capacity of the underground metro increases, bringing higher revenues.

The basis of the improvements in signalling systems is radio Communication-Based Train Control (CBTC) systems. The CBTC systems allow for closer integration with other systems, which further supports overall efforts to improve energy efficiency, and life-cycle planning and performance.

Alstom is part of a group supplying a new signalling system to Metrolinx, the transit operator for the Toronto region; Metrolinx's assets include metros. The signalling package being contributed by Alstom to the package is Urbalis – a CBTC system also used on some metro lines Amsterdam, Lille, Milan and M

GE Transportation is to supply its CBTC system – Tempo – for the joint signalling and control systems on the Thomson and Eastern region lines of Singapore's metro. As part of a

package that also includes supply of platform doors, the Tempo system is to be introduced in three stages starting from 2019.

Thomson Line is 30km long, entirely underground and will have 22 stations and six interchange stations. It is to be completed in 2021, and will connect with four other lines owned by Singapore's Land Transport Authority (LTA) – East-West, North-South, Circle and Downtown.

## TRACKS

To improve speed and accuracy in tracklaying, Alstom has introduced its Appitrack system. The new system reflects the wider approach of seeking less interruption to transit infrastructure systems, and hence more productivity – passenger journeys and revenues versus downtime and costs – from the assets.

The system can be used in metro tunnels as well as for surface tracks, says the manufacturer. Features of Appitrack, therefore, includes less excavation need to place the system into a surface and so less construction time; Alstom says costs of tracklaying with the system are lower than methods used before.

In terms of productivity, and including underground works, says Alstom, the system is capable of laying up to 300m of metro track per day

Below: Inauguration of a station on the Budapest Metro



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 toneill@systra.com  
 Steve Higham  
 shigham@systra.com  
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## HOT PROGRESS

Fire safety and evacuation are making further advances in metros.  
 Report by Patrick Reynolds

**F**ATHI TARADA, managing director of tunnel and fire safety consultant Mosen, says the provision of combustion-resistant rolling stock, and that can be easily evacuated, is crucial in metros. He highlights the recently published EN 45545 to specify engines and carriages.

Tarada notes, though, that it will take time to shift all rolling stock over to higher standard fleets, which therefore presents some ongoing risk – despite underground railway tunnels and stations being, he says – ‘without any doubt, generally safe.’

Karl Fridolf, a fire safety researcher with SP Technical Research Institute of Sweden, says the self-rescue principle ‘is essential’ when discussing evacuation of underground transportation systems.

The key to the metro design would then be to enable passengers, in an emergency, to ‘evacuate to a safe place’ with the technical installations of the subway system providing them sufficient help to do so. No waiting for the arrival of emergency services personnel; instead, the design – the designer – must show how successful evacuation can be achieved under different scenarios.

Fridolf says there are many different technical installations related to life safety, and their choice and use differs between projects. Systems can include emergency exits (including those in tunnels), exit signage, fire alarms, smoke extraction systems, and sprinklers.

### WATER

Armin Feltmann, sales engineer on tunnel systems with water-based fire safety systems manufacturer Fogtec, says fire loads have changed in recent years which consequently demands improved fire safety measures in metro stations.

Feltmann says there are, basically, two protection concepts

in approaching fire safety in metros and these focus on the rolling stock and the infrastructure, respectively.

With respect to infrastructure, fixed fire fighting system (FFFS) can protect station structures. The FFFS is based on high pressure watermist technology, with nozzles and pipework installed above the railtracks. The watermist is designed to minimise the effects of the fire, suppressing it through fast activation (by using clean water, rapid release is possible without danger or delay), reducing heat radiation, and cooling the gases and smoke which reduces their volume, thereby also cutting down the load on the ventilation system.

The combination of benefits of the suppression system, which chokes off the fire and helps contain the area being affected, helps passengers evacuate and fire fighters gain critical access – nearer to the source of the incident, and sooner. The containment also minimises the damage to the station infrastructure, and therefore downtime for repairs – ‘even in the case of severe fires,’ says Feltmann.

Fogtec’s technology is also a key component of the FFFS system that helps to manage fire safety in one of the world’s longest underground rail links – the Channel Tunnel. Like on that giant

Below: Fire safety personnel in a training scenario



transport scheme, watermist systems can be retro-fitted in urban transit networks like underground metros – ‘especially when there is only little space available,’ says Feltmann.

Although retro-fitting in any engineering context may present its own challenges, the possibility to introduce the watermist system, for example, could offer potential cost savings compared to other approaches, he suggests. Key factors in the possibility to do so come from infrastructure protection and less ventilation capacity being needed, says Feltmann.

Recent implementation of the watermist system in Budapest saw metro operator BKV retro-fit the system into nine stations of its M2 line. BKV introduced the system from the outset in the design of 10 stations on the M4 line. In addition to the main platform areas in stations, key sections to be protected by watermist systems include escalators, cable tunnels, and the control and inspection room.

#### SYSTEMS

Draeger takes a broad, integrated systems-based approach to safety management in tunnelling projects, including provision for dangers of toxic gases and fire safety – during both construction and operational phases of an infrastructure scheme, such as a metro.

During the construction phase, a variety of equipment can be in place to help safety, such as refuge chambers, medical equipment, fire trucks and ambulance trains. For this phase, and operations, there can be monitors (including access to tunnels) and various detectors (gas, smoke, infrared).

Refuge chambers are being adapted from the mining sector to play an increasing role in many types of tunnelling projects, and would help in a variety of risk scenarios. Manufacturer MineARC Systems has seen its refuge chambers used as part of safety solutions on metro projects in Kuala Lumpur and Doha. Other manufacturers include Strata Worldwide.

MineARC notes it is possible to incorporate refuge chambers into transportable standby safety systems during the operational life of tunnel projects.

#### TESTING, TESTING...

Use of the assets needs to be coordinated with effective operational rules – eg a train on fire should not stop but continue, at a pre-determined control speed, to the closest station to

### Fire Safety Research

Recent research in fire safety in tunnels has included Sweden's "METRO" project for subways, and Germany's "Safety of Life in Tunnels II (SOLIT-2)" – which focused on roads though took information from the Channel Tunnel. Both research projects completed in 2012.

Haukur Ingason, a senior fire safety researcher with SP Technical Research Institute of Sweden, says key outcomes of METRO included heightened awareness of high heat release rates and arson risk.

While there hasn't been further research so far, SP has sought that the follow up should consider risks around terrorism, and possible coordinated attacks, such as: terrorist use of accelerants and/or small explosives; design weakness of present subway systems; improved evacuation strategies; and, enhancing strategies and equipment for first responders.

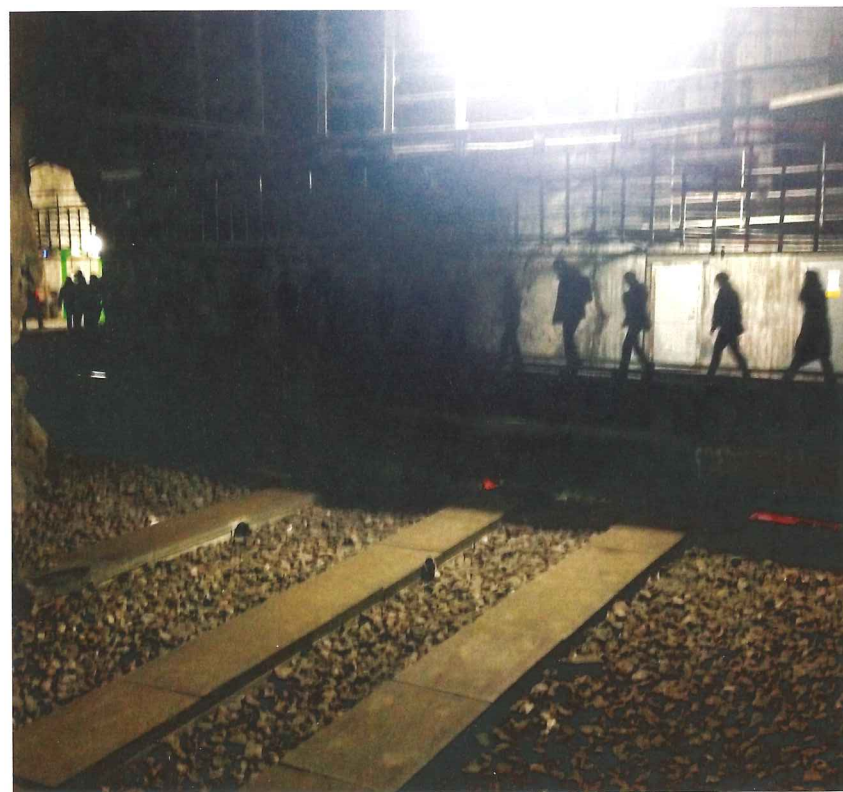
While focused on roads, one of the interesting conclusions of SOLIT-2 was that water-mist systems might 'allow for a higher safety level and savings' in other, conventional, equipment also used in fire safety solutions. The report outlines ways for fire tests to help in layout design for FFFS on a project.

evacuate its passengers.

But when testing people in a smoke-filled space, as could be experienced by passengers in a tunnel or possibly having been delivered to a station platform, the emergency criteria must take-in further aspects, including, and not least: safety is in the eye of the beholder.

If people are thrown into a situation, what might they think they see? The mind tries to make sense of the world through patterns, and in split seconds what might be constructed in the mind, and believed, may well be acted upon.

Fridolf tells of a test where some people moved sharply away from an exit fitted out, from the design concept, to have green and white halogen spotlights. Why? In debriefings, the people – only aware they were in a smoke-filled tunnel – said they thought the lights were on the front of a train. Not a door to safety.



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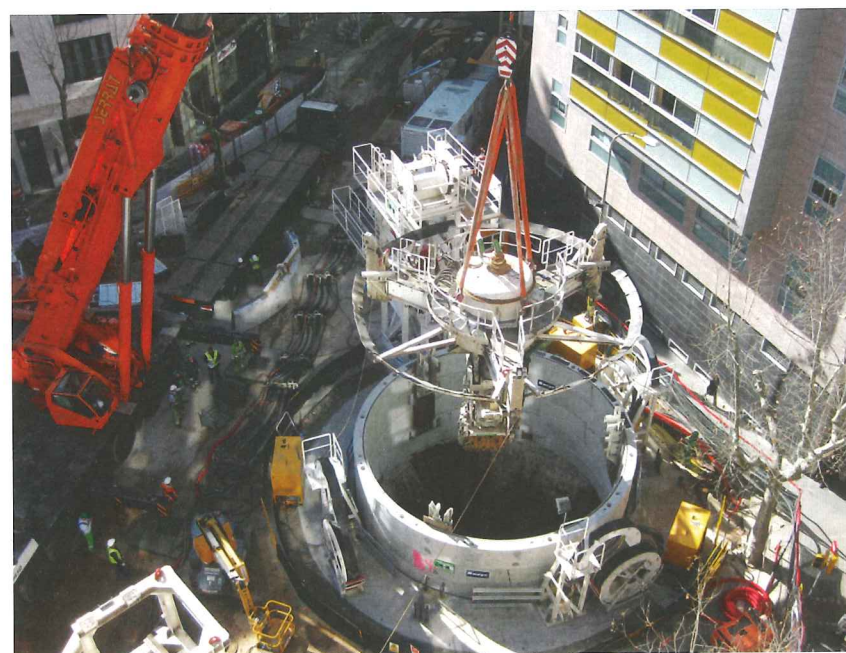
# FEEL THE FLOW

Ventilation needs are vital when building and operating underground metros.

Report by **Patrick Reynolds**

**V**ENTILATION IS crucial for health, safety and environmental conditions in an underground environment. In the case of metros, sufficient ventilation is needed for tunnellers and plant in possibly dusty, hot excavations during construction, and later during subsequent train operations to provide comfort to passengers and crew, including reducing the effects of heat from rolling stock and equipment.

Solutions to the ventilation challenge can see fans of various types mounted in different general metro tunnel spaces, and some featuring as part of smoke extraction solutions in fire safety planning. But significant, dedicated spaces can also be constructed to support a ventilation design, such shafts, some of which are now being constructed with a new type of vertical boring machine, such as underway in Moscow metro, and previously in Naples.



*Above: Herrenknecht vertical borer on a metro ventilation shaft*

*Below: CFD analysis image of smoke ventilation in a metro station*

## PROVIDING A BLAST

Examples of fans provided to tunnel and metro projects include equipment from manufacturers Pollrich Ventilatoren and Compact Filter Technik (CFT), respectively.

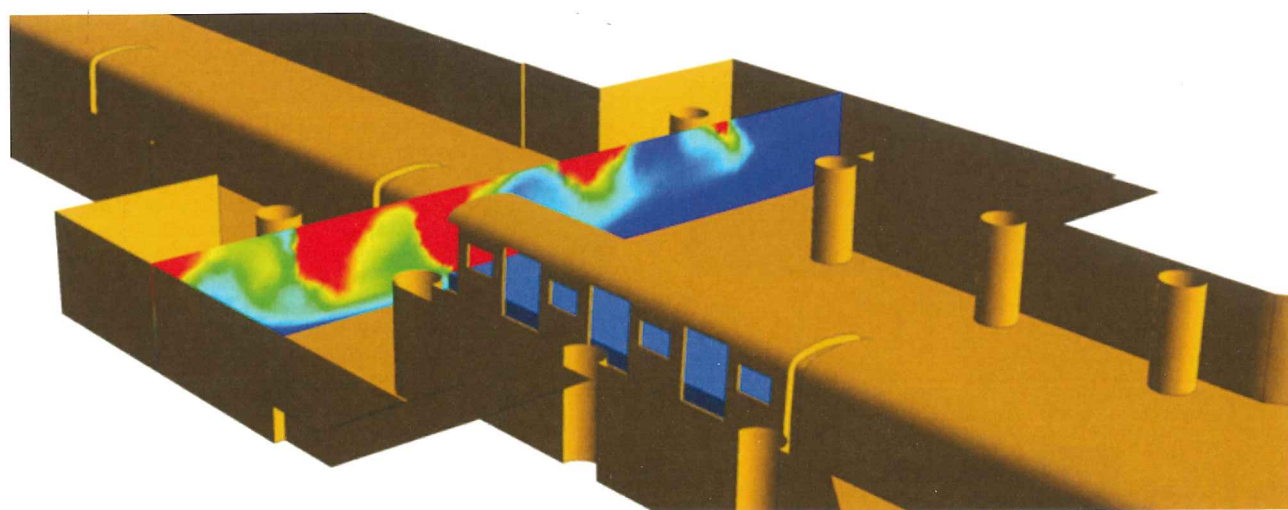
Pollrich says tunnel ventilation is used for daily ventilation in metro tunnels and stations, and air clearance in emergencies to support safe evacuation. The firm says such fans are reversible, fabricated up to 2.5m diameter, and both the flow rates and pressures are high. For durability, the impeller blades are made of stainless steel rather

than aluminium because experience has shown the latter are susceptible to damage instigated

The company adds that, while consultancy firms usually perform the metro tunnel ventilation design, equipment suppliers are usually asked to verify pressure drops; the verification can be done sometimes by manual calculation or can be achieved by computational fluid dynamics (CFD) analysis on computer.

Pollrich supplied fans to Lines 1, 2 and 3 of Warsaw Metro – a total of 34 fully reversible smoke units, each up to 2m diameter.

CFT, and also Korfmann Lufttechnik, have supplied fans and ventilation to a wide variety of tunnelling projects of different scales. The projects have included urban transport schemes like metros with projects in France in recent years.



## GETTING DOWN TO IT

An advance in shaft sinking technology is making an inroad in construction of metros in congested urban settings. The challenge is how to build shafts at key points along the alignment of a subway line where there is little space on the surface from which to work.

Herrenknecht's Vertical Shaft Sinking Machine (VSM) system is being used on an increasing number of metro projects, such as in Moscow, Naples, the company says. The cluster of works in Moscow has increased to six vertical shafts, a spokeswoman adds. The shafts are 5.7m i.d., the depths 65 to 75m, and geology is through fill then underlying hard and cohesive clay.

The vertical construction system can be used for shafts needed for ventilation or provision of emergency evacuation, the company says. This was the case on Line 1 of Naples Metro where 4.5m i.d. shafts, up to 45m deep, were constructed.

The VSM can be used in soft, stable soils with compressive strengths up to 80MPa.

It is a vertical roadheader drum on a telescopic boom, and excavation is remote-controlled. Mucking out is performed hydraulically using a submersible pump in slurry, and a surface separation plant. The shaft is sunk as excavation proceeds, with precast rings added at the surface but the rate of lowering is controlled by a combination of steel strands and hydraulic jacks.

On rail transport tunnels passing below cities, the total number of shaft built or under construction is approaching two dozen. The tally includes a few shafts sunk at either end of the Barcelona-Girona high speed line, in Spain, to depths of more than 50m.

Herrenknecht says that experience of more than 3000m of shafts using VSM in various settings indicates the system is achieving up to 5m per 12-hour shift, depending on diameter and geology. The 5m rate was achieved on dayshifts on Naples metro, allowing a shaft to be completed in about three weeks. In Moscow, each shaft has been completed in about four weeks with works round-the-clock.

## VENTILATION AND FIRE SAFETY

Water mist-based fire safety systems are able to significantly reduce smoke, which benefits ventilation system design, says Armin Feltmann, tunnels specialist with manufacturer Fogtec. He adds that this benefit is especially important in older metro stations that have only limited space to extend their



*Above: Herrenknecht vertical borer on a metro ventilation shaft*

*Below: Pollrich fans in operation at Warsaw metro*

ventilation system or establish more emergency escape routes.

"In this case a water-mist system can be considered a valuable option to increase the safety level," he says.

Feltmann adds that the ventilation system "thus does not need to be upgraded" – or not so much – "and other measures can be compensated," such as additional emergency exits.

Fathi Tarada, managing director of consultant Mosen, says the 'most effective arrangement' for smoke control, in his view, involves full-height platform screen doors along with other solutions, such as mechanical smoke extraction. Full-height doors would protect passengers from the effects of smoke and fumes, he says.

But he emphasises that great care be spent in specifying fire safety and ventilation scenarios. This is needed due to the complexity, and range of risks and reactions, when trying to develop ways to achieve appropriate responses to occur.

This adds to the challenge of using analytical tools, like CFD analysis, to simulate smoke movement in underground stations; modelling results are only as good as the underlying assumptions, he says.



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# METRO POWER

Metros are power hungry, but opportunities exist for energy and cost efficiency.  
Report by **Patrick Reynolds**

**P**OWER SUPPLIES are vital to underground metro developments during construction as well as passenger operations, and efficiencies in performance and cost are increasingly sought and being delivered.

The energy supplies are needed for excavation and pumping equipment during tunnelling, and to power trains, lighting, signalling, controls and emergency systems during the operational phase – and to also for ongoing groundwater management, where required.

Various efforts are delivering greater energy efficiency among these challenges, and include products and systems from companies, such as ABB and Alstom.

In addition, there is potential to reduce energy demand for ventilation through greater take up of geothermal cooling in tunnel linings.

## TRACTION AND RECOVERY

Among key areas of metro-related work by ABB and Alstom is improving energy efficiency from the capture and storage of braking energy of trains, and more effective traction power supply systems. The improvements bring economic as well as environmental benefits by reducing costs and carbon emissions.

Lower power needs to operate, and so fund, could help boost the attractiveness of potential metro schemes in developing economies where electricity sectors are also developing.

## ABB

ABB's Enviline system is a suite of products for power, protection and energy management systems for DC traction power substations. It says the system can help to reduce total energy consumption in DC rail transit systems by 10 per cent to 30 per cent.

Recently, in the US, ABB was awarded a second contract from Southeastern Pennsylvania Transit Authority (Septa) whose assets include metros. The second Enviline package is to be a hybrid system to both recover braking energy from DC grid and also (using inverters to switch to AC) to sell the energy into the local grid, thereby delivering so-called ancillary services – in this case, frequency regulation support.

In UK, enhanced substation performance in the London Tube system is being provided by ABB's Relion system, an intelligent electronic device for protection and control.

The Relio620 is used to improve reliability and continuity of uprated power supplies in the underground

*Below: LED lighting at Aumale station, Brussels*



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metro system.

Also in UK, Network Rail has ordered three traction substations from ABB to support future Crossrail trains. The system allows sections of line power to be isolated for inspection and maintenance.

**Alstom**

Alstom's key system for increased energy efficiency in metro power supplies is the Hesop package – a reversible power supply substation.

The Hesop system focuses on recovering energy from train braking and, in turn, reduces heat dissipation and what would have been the consequent ventilation demand in a tunnel.

It also optimises energy use for trains' traction mode, which Alstom says can allow for fewer electricity substations and associated costs.

Last year, Alstom's Hesop system began to be introduced to the metro systems in Milan and London – a trial installation on the Victoria Line, to gain more energy efficiency and to reduce temperatures in the entirely underground route).

**RECOVERY IN RIO**

Energy recovery is also a feature of a research initiative by the contractor constructing the West package of Line

**Light Savings**

LED lighting is taking a bigger role in illumination of metro stations, and recent examples includes Schreder's equipment installed in Turin and Brussels.

Schreder points to the lighting solution for the Porta Susa station in Turin having been completely met using LED lights – and that such a full solution, in 2008, was a world first and has paved the way for more use of LED systems in metros.

The Turin project saw LED systems retrofitted to bring improved lighting, energy savings and durability, which help cut costs of energy electricity demand and downtime due to the more frequent maintenance needs of the previous system in the underground station.

Schreder supplied its Astral-LED lights to Porta Susa, which is destined to be a significant interchange station for metro and high-speed rail travellers. Each Astral-LED comprises 30 LEDs, and the unit were fitted into the existing cable trays which also support the tannoy and CCTV systems.

A full LED lighting solution was also retrofitted into the Aumale metro station, in Brussels. Schreder again installed the Astral LED system, which it says doubled lighting levels while halving energy consumption to 14kWh per luminaire strip – cutting costs, carbon emissions and, again, maintainance needs.

At Aumale, a dimming system is employed when passenger zones are not being used. On some surface rail station in the UK, Schreder has also fitted motion sensors on platforms to reduce lighting needs when no-one is present, it adds.

4 in Rio de Janeiro.

Line 4 is extending the city's metro system towards the 2016 Olympic zone, improving overall capacity and should help reduce traffic congestion. The West package is being constructed by a JV led by Queiroz Galvao and Odebrecht.

Tunnelling on the West package is by drill and blast with multiple drives for the twin tube metro link.

With a major ventilation system to serve simultaneous drives, a key initiative from the JV is to test the backflow of air to recover energy

*Below: Full LED lighting solution for metro station in Turin*



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# DEVELOPING CHOICES

Metro tunnel construction looks to both segmental rings and SCL. Report by **Patrick Reynolds**

**S**EGMENTAL PRECAST concrete rings and sprayed concrete lining (SCL) dominate the construction of metro tunnel structures, the former for running tunnels while the latter has more flexible opportunities in tunnels, stations, access passageways, and even large junctions – such as the landmark works at Stepney Green on the Crossrail project. Handled by the Dragados/Sisk JV.

The greater inroad enjoyed by SCL into the UK and international tunnelling sectors comes from technological advances, and offers the possibility for both larger and more creative underground space development.

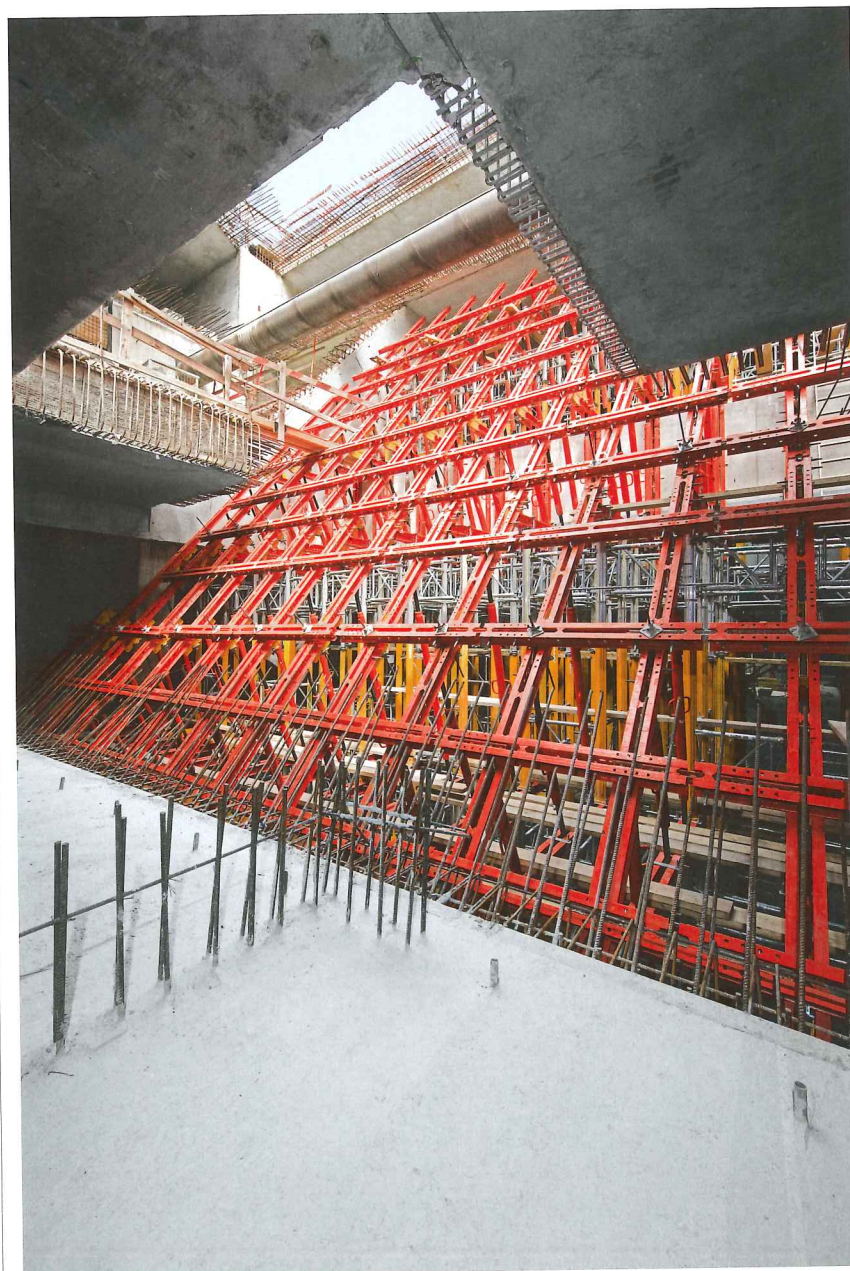
But R&D is also bringing fresh opportunities to precast segments through various concepts, such as long tunnels being integral to giant geothermal cooling systems – benefiting both the tunnels and surface structures. SCL can take on the geothermal cooling function too.

Not to be left behind, temporary works are offering more solutions to build large underground spaces and varied construction needs. An example of the former is Peri's systems for supporting construction of the large, sloping ceiling in a spacious underground metro station in Budapest; for the latter, an example is Peri's provision of a multi-level system to sit inside, and execute numerous works, in a cutting for Seattle's subway.

## SCL

A milestone in SCL use in metro projects is the Stepney Green running tunnel junction on Contract 305 of the Crossrail project. Whereas in the past the link-up would have employed step-plate junctions with segmental rings, various developments in materials, analyses and ground monitoring capabilities have enabled more ambitious and larger-scale use of the SCL method; in this case, the project also involves breakout from a box structure.

Key firms involved in SCL at Stepney Green are designers Mott MacDonald



**Above: Major formwork solution for lining of underground metro station in Budapest**

with Gall Zeidler, and contractor Dragados-Sisk JV is supported by OTB Engineering. Their work is discussed in a just published volume of ICE papers (see reference).

For SCL works elsewhere on Crossrail, notably at Farringdon station, Dr Sauer is supporting JV contractor BAM Ferrovial Kier.

In addition, on the London tube system, Dr Sauer has been working on numerous other complex SCL works, including upgrades of Tottenham Court Road and Bond Street Tube stations.

## STEPS IN SEGMENTAL LINING

Erected behind TBMs, the precast concrete rings rely on the accurate, effective and timely manufacture off-site to stockpile according to the needs of the tunnel alignment

## Rings that bind them

SCL and precast segmental lining may dominate metro tunnel construction and feature in aspects of station building, but it wasn't always so.

Earlier tunnel systems featured much use of cast iron rings. These existing structures need to be monitored for behaviour and integrity as increasing amounts of refurbishment, upgrades and expansion works are undertaken underground in established assets, like the London tube system. Maintenance of linings is also vital to minimising groundwater seepage.

In the UK, some key research projects into existing tunnel linings are being performed by Imperial College and the University of Cambridge.

Imperial has worked with Crossrail (see references) on the effects of new, neighbouring excavations on older, cast iron rings in London Clay, and also segment removal for related access

upgrades. The studies involved instrumentation and monitoring. Some of the works are part of a programme funded by the Engineering and Physical Science Research Council (EPSRC).

Cambridge's Centre for Smart Infrastructure and Construction (CSIC) is looking at ways for civil engineering assets, such as underground metros, to benefit from innovative use of emerging technologies in sensor and data management. Particular systems being investigated are fibre optics, micro-electro mechanical systems, wireless sensor networks and energy harvesting systems to power gauges. CSIC's activities in 2014 included performance monitoring in Crossrail, on some new works as well as an old rail tunnel located below the path of TBM bores. Future work is planned to include development of a maintenance planning tool focused on handling groundwater seepage problems when planning asset management in the London tube system.



**Above: Stepney Green junction Crossrail eastern section**

as well as planned progress rates, which calls for spot-on logistical planning on-site.

CBE, the France-based segment mould and carousel manufacturer, says trends in production include the use of new connecting devices, gaskets, fibres and mix designs, including self compacting concrete. A further strong trend on moulds is 3D checking and tolerance control systems.

Underground metro construction in congested urban environments also present challenges to logistical management in the timely supply and storage of segments. To help ease the challenge, Herrenknecht subsidiary VMT developed the Segment Documentation System (SDS) which is being used by Herrenknecht Formwork Technology. SDS was used on Prague metro, and is currently employed on the Koralm rail scheme.

In the operational life of the metro, the tunnel lining needs to be highly effective for long-term performance while also having the capability to deal with sudden problems, such as fires.

Fire safety design for segmental lining on Crossrail is discussed by consultants Atkins, Arup and Tunnel Consult in the volume of ICE papers (see references). The Crossrail design phase began with used thermal properties of materials in segment tests for the Channel Tunnel Rail Link; then, Crossrail

ran test programmes for each of its three concrete mix designs, and these were followed by full-scale fire tests prior to commencement of the construction phase.

## GEOTHERMAL - FOR SEGMENT/SCL LININGS

The concept of geothermal lining of tunnels is to extract excess heat energy, but they can also be employed to cool underground space. The associated tubing systems (with circulating heat transfer fluid) can be installed in segmental precast concrete rings as well as between shotcrete layers in SCL tunnels.

Arup was involved in the planning to use Rehau's geothermal system in on Crossrail's segmental lining. Rehau worked previously with contractor Zublin and to develop the patented system – EnergieTubbing – for the concept. A key, early proving project for the system was the U6 metro scheme in Stuttgart; the contractor on the shotcrete-lined project was Wayss & Freytag and Max Bogl.

There are options of closed loop and open loop systems for the geothermal lining. The closed loop systems can be used on metros, whereas open loops are more suited to long rail tunnels. Depending on ground conditions and tunnel temperatures, it is estimated that the energy yield from employment of the geothermal lining could be 10W-30W/m<sup>2</sup> of tunnel cross section. Recovered energy can be used above ground

## References

"Crossrail Project: Infrastructure Design and Construction," Vol 1; ICE Publishing; 2015. Edited by Black, M; Dodge, C; and Lawrence, U. Foreword by Dulake, C.

# LIGHT RAIL REALISED

This series of articles takes an in-depth look at Seattle's University Link light rail extension as it nears the end of its underground construction contracts

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Itaquas

As part of a larger light rail system, Seattle's University Link (U-Link) project will connect downtown Seattle to the University of Washington with two new stations. The USD 1.9bn project is expected to start service in 2016.

Among the many challenges of tunnelling in an urban environment, the project also required TBM mining through a section of the Interstate 5 freeway, excavation of 20 cross passages, and that's not to mention high hydrostatic pressures, steep gradients, mixed face conditions and two aquifers that weren't exactly located where anticipated. It has been a very successful program that saw a number of innovations to deal with technical challenges along the way.

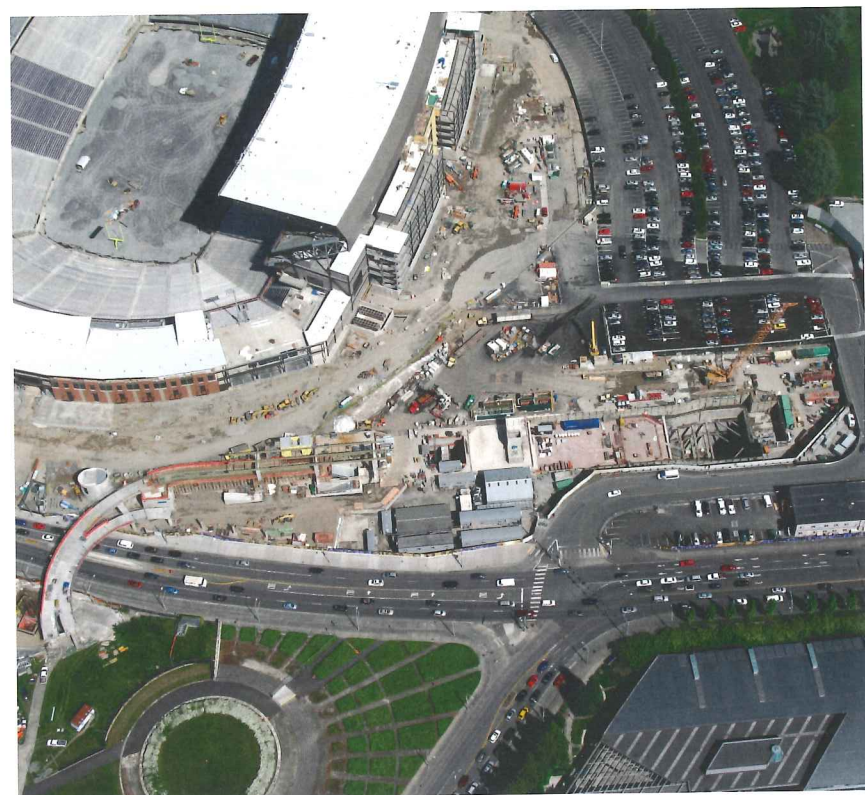
Sound Transit, the agency in charge of rail, bus and commuter services in the Seattle region, bid the contracts for twin bore tunnels of 6.4m excavated diameter in two different packages: U-220, awarded to a joint venture of Traylor Brothers/Frontier-Kemper (TFK), and U-230 awarded to a joint venture of Jay Dee/Coluccio/Michels (JCM).

U-Link is a 3.15-mile (5.07km) north-south light rail extension between downtown Seattle to the University of Washington. The USD 1.9bn project is expected to start service in 2016.

Sound Transit bid construction for twin bore tunnels of 6.4m excavated diameter in two different contracts: U-220, awarded to a joint venture of Traylor Brothers/Frontier-Kemper (TFK), and U-230 awarded to a joint venture of Jay Dee/Coluccio/Michels (JCM). See the side bar on page XX for a complete list of contracts for the U-Link project.

"My biggest appreciation has been the continued cooperation of all our contractors working together on to help our project teams achieve a number of our goals related to safety, quality, costs and schedule," say Joe Gildner, Sound Transit's executive project director for U-Link.

"Given the number of contractors concurrently working on our project along with several major third-party



Above: Aerial view of jobsite

contractors in proximity to our work, I truly appreciate that we have not had any major incidents or issues develop. This is testimony to open communication and cooperation particularly the core team members working in the field. This includes the various project managers, general superintendents and crew superintendents working for the contractors (and their subcontractors) along with our construction managers, resident engineers and assigned staff."

The construction management consultant for U-Link is Seattle Tunnel and Rail Team (START JV), led by CH2M HILL with Jacobs Engineering. Northlink Transit Partners (NTP) is responsible for the design and is lead by Jacobs Associates with HNTB/AECOM, KPFF (for civil structural) and Dr. Sauer (for SEM). The START JV is also working on Northgate Link, the next portion of Seattle's light rail expansion after U-Link.

## INTERSTATE 5

In its route across the three western United States, connecting drivers to both the Canadian and Mexican borders, Interstate 5 (I-5) passes through downtown Seattle.

With a light rail expansion planned to connect downtown Seattle to more northern parts of the city, it was determined the twin tunnels of the University Link (U-Link) project would cross beneath the interstate.

This downtown Seattle portion of I-5 was built in the 1960s in a cut, initially without any retaining walls. The ground started to move and huge pile retaining walls were eventually added, explains Paul Gasson of CH2M Hill, "The reality is you end up with these four walls of piles that actually become the

main retaining walls of I-5, and then you have the smaller walls of the on and off ramps."

To keep the U-Link tunnels at a workable depth, the alignment, and in particular the TBM, would need to go through the interstate's cylinder piles—the biggest being 10ft (3m) in diameter with embedded steel plate girders. Not a small feat, and one that was successfully realized by cutting out the piles and steel I-beams where the alignment passed, and creating a new foundation through which the TBM could and did excavate.

"This was probably the most sensitive bit of mining on the alignment because they're close to half a diameter, to the surface of I-5," explains Gasson.

## ADVANCED OPTION

U-Link's tunnel alignment is dictated by an existing bus tunnel immediately to the west of I-5, which is tunnel's southern terminus. There is nowhere else for the tunnel to go, not to mention the already steep grade coming down from Capitol Hill Station. There is no room to come up after I-5 and to connect to the bus tunnel if the alignment went deeper than the piles. The distance between the bottom of I-5's pile and the invert of the tunnel alignment is some 15ft (4.5m).

"The one option that was considered," says Gasson, "was whether this pile cutting should be part of the U230 contract. But bringing it forward one year as an advanced works contract took much of the risk away. If anything went wrong or if we had a delay it was never going to delay the tunnelling."

This enabled the project to select a specialist contract for shaft and drilling operations. Sound Transit awarded the U215 contract to Condon Johnson and Associates in January 2009 to remove the I-5 cylinder pile structures in preparation for the U230 tunnelling contract.

Condon Johnson started on site in May 2009 and excavated four shafts, two on either side of I-5, down to the depth of the tunnel alignment and cast a permanent concrete base slab in each one. The contractor carried out the work among the I-5's on/off ramps. Condon Johnson had 50-week allowance for the closure of the on/off ramps, starting immediately after Memorial Day. The piles were progressively removed exactly on the alignment of the TBMs, still remaining everywhere else. Tie backs were installed into the remaining retaining wall. As the shaft was excavated down the contractor did a cast in place lining.

This is transferring the loads from the existing piles into the new shaft lining, which enables the little sections of pile to now become redundant.

"Imagine a chair with the back being pushed against a wall, and that really was a concrete box in the ground that actually braces the retaining wall and enables sections of the piles to be burned out," Gasson explains.

"So you end up with a concrete shaft with a very substantial cast in place lining all tied together with the piles that remain in place. And then the piles were locally burned out and cut out along the tunnel alignment, then the shaft itself was filled with CDF and then a concrete lid was put on the box. Now you've effectively got a reinforced concrete box full of CDF that the TBMs will drive through later."

The I-5 shafts were up to 60ft deep, with the depth dictated by the permanent tunnel invert plus 4ft of TBM driving clearance and 3ft base slab. Running parallel to the tunnels, the length of each shaft was dictated by the distance between existing piles, of the existing on/off ramps, and that ranged between 30ft and 40ft.

The internal, lined, width of the shafts (perpendicular to

## U-Link contracts

### U-215

- I-5 Advanced work
- Shaft excavation
- Condon-Johnson & Associates
- May 2009 to March 2010

### U-220

- TBM tunnels
- University of Washington Station to Capitol Hill Station
- Two Herrenknecht EPBMs
- Traylor Bros/Frontier Kemper JV
- Commenced January 2010

### U-230

- TBM tunnels
- Capitol Hill Station to Pine Street
- One Hitachi-Zosen EPBM
- Jaydee/Coluccio/Michels JV
- Commenced January 2010

### U-240

- Capitol Hill station
- Bottom-up construction
- Turner Construction
- Commenced 2012

### U-250

- University of Washington Station
- Structure and finishes, top down construction
- Hoffman Construction
- Commenced April 2011

### Other contracts include:

U-210—Advanced utility relocation for UW Station (Granite Northwest, Inc.); U-211—Demolition and environmental remediation for Capitol Hill Station (NRC Environmental Services, Inc.); U-260—Track work; U-820—Light rail vehicle storage yard expansion (RailWorks and L.K. Comstock); U-830—Rail systems and track (Stacy and Witbeck, Inc.)

the tunnels) was 30ft. The reinforced concrete windows for the TBMs to pass through were 30ft wide (the internal width of the lined shafts) by 28ft high giving a nominal 4ft of driving clearance all round. The machine excavated diameter being a little more than 21ft.

Condon Johnson used thermic lances—a cutting tool that reaches very high temperatures—to cut the steel girders inside the cylinder piles. Birmingham, Alabama-based Oxylances supplied the tools.

Gasson says his biggest concern was if there was any movement on the pile walls during excavation. "And the reality was there was absolutely no movement on the pile wall during the excavation."

He later adds, "this is the wall the TBM has to come down through later. It's always going to be 'if there are movements now there might be some

more movements later. When I-5 was originally constructed the ground did actually start to slip in this area. That's why these cylinder piles were put in here in the first place."

Looking at the cross section of the alignment (page XX), the area of ground underneath I-5 shows where there has been historical movements in the soil such as fractures, slipping sides, slip planes and in the soils.

"Wherever you've got something like that that's happened in the past you're always wary of that when you tunnel through or excavate," he says. "Basically wall movement was the main concern, and particularly because of historical nature of the way the ground had moved during the original construction. And you never really know what those planes are going to be like."

"The reality was the retaining wall itself was oversized—the size of these cylinder piles—and the design for our shafts was so conservative that nothing ever went anywhere."

Condon Johnson completed its contract early in May 2010.

**TBM EXCAVATION**

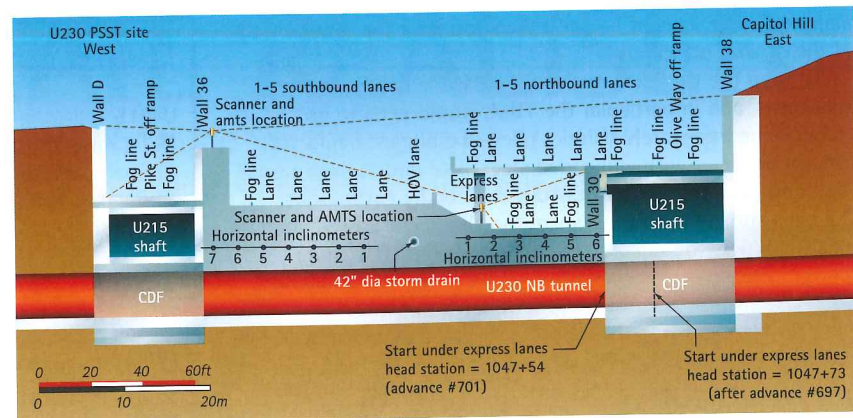
Contractor JCM started working on site in January 2010 for the TBM tunnels from Capitol Hill Station to Pine Street Stub Tunnel. The I-5 undercrossing occurred in the last 300-400ft (91.5-122m) of the two one-mile drives. Using one TBM for both drives, a Hitachi Zosen machine launched twice from Capitol Hill.

Between each CDF-filled shaft the 6.4m diameter TBM had about 14ft (4.3m) of cover under the expressway. There was approximately 30 rings (150ft [45.7m]) of native ground between the east and west shafts filled with CDF.

"The crossing of I-5 was definitely a challenging proposition," says Glen Frank, project manager for the JCM JV. "There was low cover, and the entire crossing was in ground that was deposited by landslides, which meant that there was going to be steeply dipping faults that led directly from the face to the bottom of the freeway."

For the contractor, there was concern that fluids would travel up these faults and end up on the freeway potentially causing a serious accident.

"The only way to prevent that from happening was to not pressurize the face, of course that was not a workable solution, because there would be no face support and we would likely have ground loss, settlement at the face and significant damage to the freeway structure above," Frank says.



Above: Summary of works on the project

For the I-5 undercrossing JCM switched to 24/7 mining on both drives. The shafts created something like a safe haven before the actual crossing where the TBM stopped for tools to be inspected before crossing. All of the TBM operating parameters changed for this portion of the alignment. And a sophisticated monitoring system was set in place.

"We started training the TBM operators, crews and engineers in the observational method of pressure balance tunneling about halfway through the first drive. We wanted to have everyone comfortable with using the TBM sensors to determine what the actual static active pressure in the ground is so that we could provide face support without over pressurizing the material in the cutterhead chamber," Frank explains.

When the TBM got to I-5 JCM was able to mine at a reduced pressure of 0.5 bar, which reduced the risk of having fluids flowing out onto the freeway, without adding too much risk of settlement damage above. The U230 TBM first undercrossed I-5 on November 15-17, 2011 for the northbound drive.

"Despite our preparation, we still experienced some fluids coming to the surface in the median where an overhead drain from the freeway deck above had washed out a 4ft deep hole, which was filled with debris," says Frank. "We determined that the fluid probably moved through a fault that was connected to the backfill of a storm sewer that was only 8ft above the tunnel and then into the hole under the drain. Thankfully the fluid didn't make it to the travel lanes of the freeway and there was no impact to the public."

For the second drive, JCM didn't do anything differently from the first, besides checking there weren't any holes in the median between the express lanes and the southbound lanes.

The first crossing resulted in a consistent 0.25in of settlement along the crossing and there was discussion about having no settlement on the second crossing. "It was decided that there was no way to do that without increasing the risk of having fluids on the freeway, and agreed that we should not change any parameters on the second crossing," Frank says.

He explains, "Having the fluid in the median on the first drive confirmed our fears that fluids on the freeway was a real concern and motivated everybody to be on board with our plan to optimize (minimize) the face support pressure. Thus we were able to lower our prescribed minimum support pressure on the entire second drive (based on our observations from the first drive) and allowed our crews more opportunity to use the observational method for pressure balance tunnelling."

The second I-5 crossing took place April 23-25, 2012 for the southbound drive and completed without incident. "But by that stage everyone had confidence anyway," says Gasson. "I would say there was less concern with the second undercrossing. Everyone was on tenterhooks the first night"

# GOING LIVE

San Francisco's Central Subway Project makes a major milestone in 2014

THE CENTRAL Subway is part of the San Francisco Municipal Transportation Agency's (SFMTA) Third Street Light Rail Transit Project. Phase 1 of the 10.9km, two-phase project began revenue service along the Third Street corridor in April 2007. Scheduled to open in 2018, Phase 2 adds 2.7km to the line, excavated at depths ranging from 15m to 45m below the city.

On June 16, SFMTA celebrated the breakthroughs for the project's two TBMs, which each completed an 8,500ft-drive (2,590m) to build the tunnels. Three subway stations will be built underground, as well as a surface-level station.

Grinding two metro-sized EPBs through urban tunnels in dense silty sand just 9.7m apart is difficult enough. Add into the mix a 13mm settlement tolerance, sensitive building structures, and live rail tracks just 3.4m overhead, and you have a challenge. San Francisco's Central Subway rail tunnels, snaking through downtown areas, were required to be driven below the existing Bay Area Rapid Transit (BART) line.

"It was a major technical undertaking, and many were skeptical that it could be done. The BART System couldn't afford to be taken offline," said Matthew Fowler, Project Manager for the Parsons Brinckerhoff/Telamon JV, which is responsible for the utility relocation and tunnel designs.

Fairly tight curves down to a 137m radius were always part of the alignment, as the result of right-of-way considerations and the desire to keep the Union Square/Market Street station platform as close to the Powell Street Station as possible to shorten transfer times to BART and the Muni Metro lines.

Contracts were awarded for tunnelling in 2011 to the Barnard/Impregilo/Healy JV, while station contracts were awarded in 2013 to Tutor Perini. It is planned to build the three underground stations after tunnelling is completed, in what will continue to require complex logistics. The Robbins Company provided the projects two 6.3-diameter EPBs.

Geological testing revealed layers of mixed ground. Approximately 4.6m of loose to medium dense sand fill over-lies 7.6m of medium dense sand with clay and clayey sand. Underlying the sand and clayey sand units is the 14m

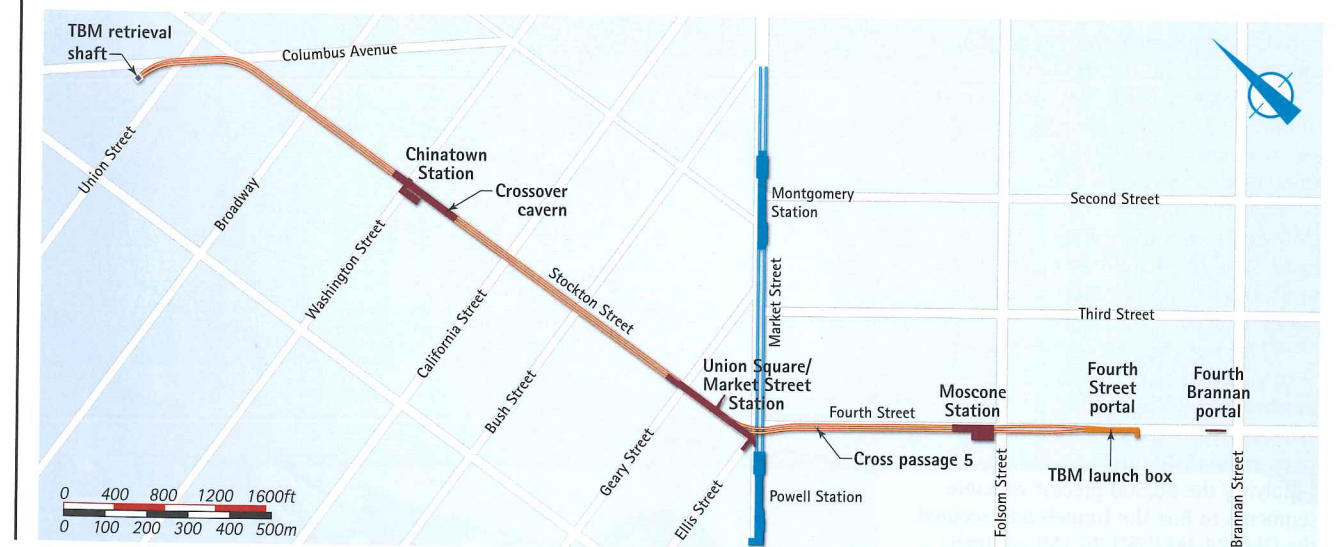
thick Colma Formation, a dense to very dense sand with silt to silty sand and beds of clay. The Colma sand is underlain by very stiff clay and dense to very dense silty sand or clayey sand referred to as Undifferentiated Old Bay deposits. Groundwater levels were measured at 9.8m below ground surface.

Once the TBMs were launched, preparations began for the complex crossing below live BART tracks. The lowest elevation of the Central Subway profile is controlled by the assumed vertical clearance to the 19.8m deep invert of the lower pair of the Market Street tunnels. Constructed between 1967 and 1970, the four 5.3m diameter steel-plate lined tunnels are used by BART and SFMTA's Municipal Metro subway systems and together serve as the underground transit backbone for San Francisco.

The Central Subway tunnels are being constructed perpendicular beneath the existing BART tunnels. Permanent support of the 5.44m inside diameter Central Subway tunnels is being provided by a single-pass, 280mm thick precast concrete segmental lining system composed of six tapered, 1.5m nominal width segments. Narrower 1.22m segments were cast for the curve sections. The circumferential joints are joined with 16 dowels per ring and the radial joints with two bolts per joint. Embedded-type gaskets supplied by Datwyler-Phoenix and designed for 6 bars of pressure seal each of the segments.

With careful excavation, minimal settlements were measured, and no compensation grouting was needed. The second machine excavating the northbound tunnel completed its crossing in February 2014, with equally successful results

Below: Alignment map for the project



# PAIR UP

Four TBMs are being deployed to build the Toronto region's new light rail line, with the first pair already underground

**T**ORONTO IS in the midst of its largest transit expansion in history. Worth CAD 5.3bn the Eglinton Crosstown project will build a new 19km-long LRT line across the city.

The new line will run along Eglinton Avenue, an east-to-west road that changes from a downtown corridor with storefronts and parking spots to a suburban arterial road over the course of the alignment. Between Keele Street and Laird Drive the line will be underground in a 10km-long twin tunnels.

Metrolinx, an agency of the province of Ontario and owner of the Eglinton-Scarborough Crosstown LRT, is responsible for planning and funding commuter rail and rapid bus transportation in the Greater Toronto-Hamilton Area, which has a population of more than 3 million. The Toronto Transit Commission is Metrolinx's agent for the project and will operate the line following completion. Ontario is funding 100 per cent of the project.

Dividing the tunnelling into two contracts, Metrolinx awarded the first package in September 2012 to Crosstown Transit Constructors (CTC), a joint venture of Obayashi Canada, Kenny Construction, Kenaidan Contracting and Technicore Underground. CTC is mining 6.2km of the tunnels, from the west launch shaft at Black Creek Drive to Yonge-Eglinton station, using two TBMs. The contract is worth CAD 320M (USD 242M).

CTC launched the first pair of TBMs in spring 2013, which are mining eastward, approximately 10m per day, and between 16m to 20m below ground.

In November 2013, Metrolinx's board of directors approved the award of the second contract for 3.25km of twin tunnels to an Aecon-ACS Dragados Canada joint venture. The contract is for CAD 177M, and will use two TBMs to build the tunnels from Brentcliffe Road to an extraction shaft located east of Yonge Street.

All four of the project's TBMs were manufactured by Caterpillar, and purchased by owner Metrolinx in 2010 at a total cost of CAD 54M (USD 41M). Local manufacturer Munro Ltd., is supplying the 88,500 precast concrete segments to line the tunnels and secured the CAD 78.2M (USD 76.1M) contract

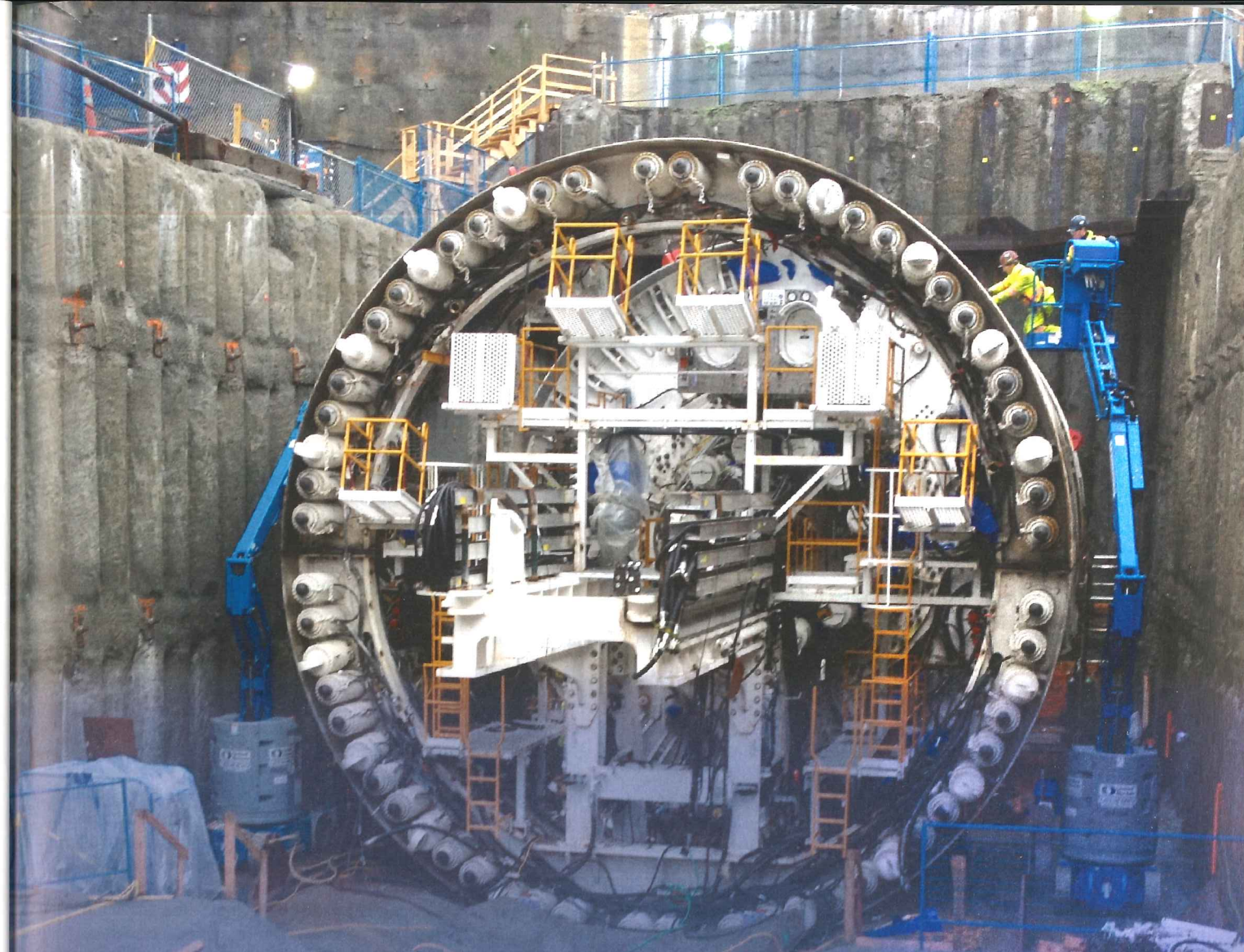
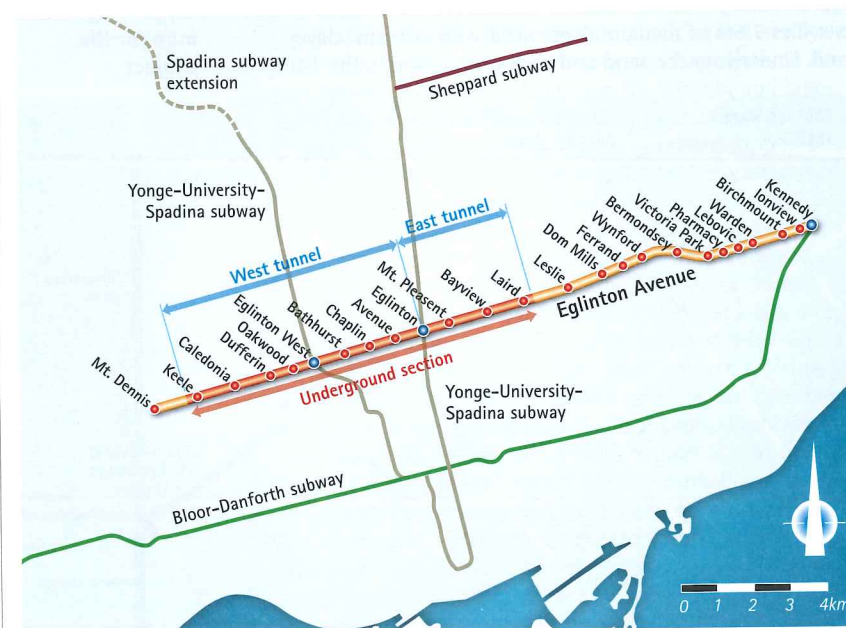
from Metrolinx in February 2011. The tunnels have a 5.75m i.d.

Eglinton Crosstown will link to three subway stations. When the first pair of TBMs reaches Eglinton West Station, a future connection to the Yonge-University-Spadina Subway line, CTC will extract them from a shaft west of Allen Road. After perform refurbishment work the machines will be relaunched to the east of Allen Road to continue tunnelling to Yonge Street. This will allow the subway to continue its normal operations during tunnelling for the Eglinton project.

As of this autumn the TBMs had mined more than 2.8km of the twin tunnels, and are approximately 700m from the extraction shaft at Allen Road.

The second set of TBMs are expected to launch soon

Below: CAT TBM and project alignment map



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# A CROSSRAIL MILESTONE

Project managers Roger Mears and Greg Reichmann look back on three years of successful tunnelling at Crossrail

EUROPE'S LARGEST construction project, Crossrail, is moving closer to its phased opening starting in May 2017, leading up to full opening in December 2018.

When that happens, Crossrail will connect Reading and Heathrow in the west with Shenfield and Abbey Wood in the east. Crossrail will add 10 per cent capacity to London's rail network, will serve 40 stations – 10 of which will be new – and will carry an estimated 200 million passengers each year.

This monumental project will have a profound effect on the way millions of people visit or transit through London every day, so it's all the more remarkable that, for the average man or woman on the street, it's been pretty invisible.

There are exceptions, of course. In 2014 an excellent three-part BBC documentary profiled the project and some of the individuals working on it. And earlier this year the Prime Minister, David Cameron, and Mayor of London, Boris Johnson, featured in the news as they celebrated the completion of tunnelling following the final breakthrough at Farringdon station.

The fact that this huge endeavour has caused relatively few ripples is a great source of pride to the teams responsible for its construction, particularly as asset protection has been at the top of the agenda. Roger Mears, project manager for the C305 eastern running tunnels contract and Greg Reichmann, project manager for the C300/410 western running tunnels, agree that third party asset protection both above and below ground has been fundamental to Crossrail's success.

## BEHIND THE SCENES

Among the many infrastructure obstacles thrown up, Mears cites having to tunnel under the Canning Town viaduct as an example. Here, the Dragados Sisk joint venture (DSJV) implemented a very sophisticated system of jacking and monitoring to compensate for ground movement.

Existing utilities also posed significant challenges: "We've bypassed a number of large diameter sewers by a very few metres so we've had to carry out sewer

lining operations, which are challenging scopes of works in their own right," said Mears. "Trying to agree what the nature of the mitigation is and then installing it ahead of the TBM passage generates a whole new package of works."

Further west, concerns from "a very important stakeholder" were of an altogether more cultural tone.

"We tunnelled under the Barbican Centre and they were very concerned about the noise impact on their concert halls from both the tunnelling and the subsequent railway operations," said Mears.

"They were quite nervous during the days, weeks and months prior to us tunnelling under, so much so that we understood when the New York Philharmonic Orchestra was going to start performing! Their fear was that concert goers would be able to hear the underlying rumblings of a huge TBM in the gaps between the beats in the music, which would be a terrible disruption."

The team was so confident that noise would be minimal that, in fact, the programme of works wasn't altered. "What we did do was change to a different type of track bed both for the construction railway laid behind the TBM and for the permanent works," said Mears. "A section of track slab will be on bearings which will damp down any vibration and prevent noise from the railway operations. For C305 we built the full track bed and the construction railway as we tunnelled and used a different sleeper design and we've had no complaints from the Barbican Centre throughout our works."

Quite the opposite, in fact. The Barbican Centre was so impressed with Crossrail they commissioned their own artwork to mark the passing of the TBM underneath the estate.

Underneath the western running tunnels the infrastructure included 18th century wells at Tottenham Court Road and Bond Street stations. "If they had been charged with water and been in a slightly different location they could have been a really big issue from a structural stability point of view," said Reichmann.

Below: TBM Elizabeth breaks through into Farringdon Station



"But our processes and tunnelling excavation sequences and methods take account of those types of obstacles and we only go forward at 1-1.5m at a time in those advances so that, if we do come across something, we haven't suddenly exposed a large section of unsupported ground."

Culturally significant buildings are very thick on the ground in this part of London. In Soho Square, for example, one of the capital's oldest buildings, the Grade I listed House of St Barnabas, had to be closely monitored for ground settlement. And access for vintage cars worth many hundreds of thousands of pounds had to be maintained at Bonham's auction house in New Bond Street.

Both of these challenges were highlighted by the BBC documentary – as was the captivating tale of "the eye of the needle" at Tottenham Court Road station where the Northern Line and Central Line of the London Underground intersect. Crossrail needed to link to this hub and negotiate sewers, pipes, cables, the Northern Line platforms and two escalators. The only option was to drive the 900 tonne TBM 850mm above the live running tube line and 350mm below the escalators.

However, Reichmann and Mears are modest about these more publicised achievements.

"The Tottenham Court Road location was tighter than you would want but in terms of managing the TBMs alignment to get it to where you wanted it to be within normal tolerances, the guys have got the competence to do that," said Mears. "They are able to steer the TBM very precisely, assuming the laser surveying technology works – which it has done."

"The BBC picked up on the things they could dramatise easily but there were so many smaller white knuckle moments that didn't come with the same drama to other stakeholders," added Reichmann.

"There were things like getting a Thames Water main monitored and secured before a TBM went under it, or getting the approvals from external stakeholders and asset owners before we started excavation of a new section of tunnel. Those one-off interfaces are very intensive in terms of the amount of time and human capital spent on trying to resolve issues."

"And working in the middle of Mayfair, where you have residents and businesses to keep happy is a challenge because the residents don't want you working at night and the businesses don't want you working during the day, so we've had to employ practical means to make sure we don't impact either. Stakeholders are rightly concerned about their assets and overcoming those trust hurdles is as demanding as the physical works."

This is where the "unsung heroes" in the background have really come into their own, said Reichmann.

"Take our compensation grouting team as an example," he said. "There are five grout shafts at Bond Street, seven at Tottenham Court Road and one at Fisher Street [there are 22 in total]. The fact that you didn't hear much about their work was because it was a success. It's those types of activities that can stop a project if they go wrong."

## PROCURING PERFORMERS

Reichmann and Mears agree that Crossrail's smooth progress has also largely been down to the "really high-spec" Herrenknecht TBMs employed on the project.

"Crossrail wrote the specs for the TBMs and gave those to the contractors to adapt and procure," said Mears. "There was no debate about leaving them to try to find the lowest possible cost solution – it was a case of 'this is what you need, this is what you are going to get'. That has been a good lesson learned."

While the eight TBMs have undoubtedly been star performers, both project managers point to the SCL work as being perhaps the most rewarding when it comes to a sense of achievement.

"The running tunnels tend to be the prizewinners when it

## Facts and figures

- Construction began on 15 May, 2009.
- Tunnelling commenced in May 2012 and ended in May 2015.
- More than 10,000 people are currently working on Crossrail, including 485 apprentices.
- Eight Herrenknecht TBMs have bored 10 tunnel drives and 42km of new 6.2m diameter rail tunnels under London.
- The TBMs had a total of 18 breakthroughs.
- Tunnelling progressed at a collective average of 38m per day.
- The fastest day of tunnelling by a single machine was 72m by Ellie on 16 April, 2014.
- The deepest point in Crossrail tunnels is 42m at Finsbury Circus, near Liverpool Street station.
- The type of ground bored through included London Clay, Lambeth Group, Thanet Sands and chalk.
- There are 10 cross passages on the eastern tunnels, six on the western tunnels and four on the Thames tunnel.
- Five portals were built – Royal Oak, Pudding Mill Lane, North Woolwich, Victoria Dock and Plumstead.
- Crossrail's tunnels are made up of more than 200,000 concrete segments, each weighing 3.4 tonnes.
- Ten new world-class stations are being built. Typically they will be 250-300m in length and have been constructed at depths to tunnel crown up to approximately 30m below street level.
- Crossrail is being delivered by Crossrail Ltd, which is a wholly owned subsidiary of Transport for London. Crossrail is jointly sponsored by the Department for Transport and Transport for London.

comes to getting media attention because they're big," said Reichmann. "The TBM purists of the world will kill me for this but I find the SCL is a lot more demanding from a technical perspective."

The largest SCL caverns for Crossrail were built at Stepney Green where two drives meet – the Z drive that goes out to Pudding Mill Lane, near Stratford, and the Y drive that leads on to the drives that run down to Abbey Wood. The caverns are 17m at their widest point, twice the diameter of the running tunnels, and have an access shaft for ventilation and emergency access and egress.

"This was a very challenging piece of construction work because it couldn't be done in a single drive," said Mears. "It was done in a double side wall drift, so the left and right central sections of the tunnel were advanced to a certain point and then the central heading was brought up to enlarge it to its maximum."

Forming the tunnel lining at the point of application, as opposed to building a concrete ring in factory conditions created different challenges.

"You have got to be really spot on and the materials have to be perfect," said Mears. "The SCL is a sensitive chemical mix including retarders and accelerators that can be affected by the ambient temperature, storage of the accelerators,

the wetness of the aggregates, where the cement has come from and so on. It's a really delicate balance and takes a lot of control and competence to make sure you have the right product and the right workforce who know how to apply it.

"The caverns were built in about 18 months, which is quite remarkable and, again, a big success story."

Crossrail has provided a showcase for SCL and Reichmann pointed out that the project has pioneered different profile and excavation control techniques that have been used in the past but have been improved. "The technique of using beamers to control excavation on the King's Cross project has been improved and all the contractors are adopting that technology to improve the product they can offer.

"There is much to learn from the materials that are being used on Crossrail, as well," continued Reichmann. "This is the first time that a sprayed waterproof membrane of this magnitude has been used in this environment. And just spraying a secondary lining of this scale after we've already installed a primary lining that will last tens of years without any settlement is remarkable."

Mears points to another example of new techniques being applied to old methods, this time where SCL turned out not to be the preferred option.

"On C305 we built our cross passages using SGI segments rather than SCL. There was a lot of debate about it but DSJV wanted to go with segments because of the surety of the products – they felt more confident in the programme if they could advance the heading knowing another segment was waiting for them."

Manhandling these very large segments presented another challenge. DSJV worked with their supply chain to design and build an erector structure that sits in the cross passage. "I've seen films of London Underground construction where the men had to lift the segments on their backs and force them into place but now that process has been mechanized. I've never seen it done before."

Mears and Reichmann both pay tribute to the contractors they've worked with on their respective contracts – DSJV for the eastern running tunnels and Bam Ferrovial Kier (BFKJV) for the western.

"DSJV have done a really excellent job – and I'm sure Greg will say the same about BFKJV in the west," said Mears. "They've been really collaborative and innovative in working out ways to build the job as efficiently as possible."

#### CONTRACTING OUT

Mears and Reichmann also agree that, in many respects, the knottiest challenges

have arisen at the interfaces between the many different contracts and sub-contracts that have made up the mammoth Crossrail project. The western package was originally two contracts, C300 was running tunnels and C410 was the station platform tunnels and concourse tunnels. BFKJV proposed bringing those contracts together in a solution that was beneficial to Crossrail and from a programming perspective.

"There was a lot of planning at tender time to make sure those interfaces worked but, as with any construction project of this scale, as time goes on programmes change and suddenly some of the elements that used to fit, don't any more," Reichmann said. "The big, ongoing construction challenge is making sure those elements dovetail – such as starting work on the Bond Street and Tottenham Court Road platform tunnels at the same time as you're trying to strip out a TBM."

"The interface between contractors is challenging," agreed Mears. "A lesson learned for everyone on Crossrail and definitely for myself is that you have to make sure you minimize those interfaces and have them at sensible points in three-dimensional space."

"It obviously makes it very difficult when you have to transit a TBM through a box that was built by someone else. It's easy to say with hindsight that maybe we could have structured some things differently but take your mind back to the when the job was first let – it was a difficult time in the industry and Crossrail was conscious it didn't want to burden one contractor but wanted to spread the work evenly among companies who were capable of doing the work."

Of course, there is still an enormous work to be done before passenger trains start running through the Crossrail link but there is a sense that now the tunnelling is finished, from a risk perspective at least, the most challenging part of the project is complete. And, with that, comes a huge sense of pride in the achievement thus far.

"Some of the platform construction is complete and the platform edge screen doors are going in so it's all coming together," said Reichmann. "Seeing that is when you think 'we were a part of that, we created the space to allow this to happen.' It's very rewarding"

Below: British Prime Minister David Cameron visits Crossrail



# PRIVATE POWER

With a massive redevelopment of the Battersea Power Station in London, a privately-funded extension to the Northern Line will serve new residents in the area

LONDON UNDERGROUND'S (LU) Northern Line is one of the oldest and busiest tube lines on the network. The line covers 58km and includes 50 stations.

The line connects the southernmost station, Morden, with High Barnet, Edgware and Mill Hill East in the north, and features a branching layout near Central London.

It is used by more than 900,000 passengers a day and more than 200 million passengers annually. By 2020, even, that number will swell with an extension in South London.

In December 2012, the UK Government agreed to a loan of up to GBP 1bn (USD 1.6bn) for LU to fund an extension of the Northern Line to the Battersea Power Station site. The work includes 3km of TBM driven tube-twin tunnels and two new stations.

Earlier in 2012 a new buyer had been confirmed for the Battersea Power Station site, an iconic London landmark along the southern bank of the Thames River. Dating back to the 1930s, the former coal power plant is currently undergoing redevelopment construction that will see the creation of 3,400 new homes, a new office quarter, a retail centre, new hotels and an entertainment district, among other amenities.

As well as enabling access to the tube for thousands more passengers, the Greater London Authority says that the transport benefits from building an extension to the Northern Line include cutting journey times from that part of London to the West End and the City to around 15 minutes, reduced pressure on Vauxhall station, relief to existing Northern line services south of Kennington and wider access to leisure and employment opportunities for local people.

LU announced summer 2014 a contractor joint venture of Ferrovial Agroman Laing O'Rourke will build the Northern line extension. The contract, worth approximately GBP 500M, will be for six years and covers the main construction works. LU invited tenders from four bidders (for the design and build contract, which involves the construction of some 3.3km of 5.2m i.d. twin tunnel and two large-scale stations, one at Battersea and one at Nine Elms).

LU says the extension will regenerate the Nine Elms area by



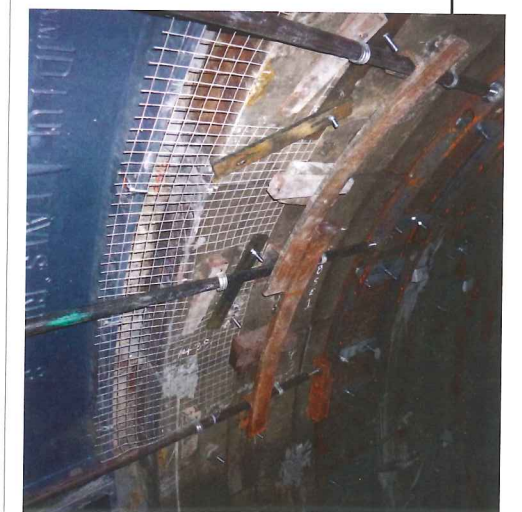
Above and bottom right: Other recent work on the London Underground includes re-lining a section of the Jubilee Line

Below: The Northern Line extension to Battersea

supporting up to 25,000 new jobs and 16,000 new homes

"As our population grows faster than any other European city, the case for stable and sustained investment in London's transport network has never been stronger," says Mike Brown, LU's managing director.

Construction is expected to start next year. The full cost of the scheme is expected to be up to GBP 1bn, which is being funded entirely through developer contributions from Battersea Power Station and other developers and, from 2016, a new Enterprise Zone



# RING UP

Four TBMs are circling Copenhagen for a new 16km metro line

COPENHAGEN'S CITYRINGEN, or City Circle Line, is just that. A metro line comprising approximately 16km of twin-bore tunnel connecting the city's main population, education and workplace centres.

Cityringen tunnelling and station works are being done under a single contract by the Copenhagen Metro Team, a JV of Salini Costruttori, Tecnimont and Seli, which has an EUR 1.7bn (USD 2.21bn) contract with client Metroselskabet.

"It is a very difficult task just to manage the vast number of locations," says Guy Taylor of client Metroselskabet. "We have a complexity of volume here with many separate designs split between hundreds of packages. An enormous challenge, but we are very well on the way and I would say progress is satisfactory. The next challenge will be constructing so many sites simultaneously. Because of the phasing of works, the important thing is to ensure delays do not accumulate."

Following the political green light to proceed on the project in 2007, and design work commencing in November that year; ground engineering works at the TBM launch sites and other worksites have been underway since the contract award on 7 January 2011. The first worksite, Norrebro Park, was handed over on 10 July 2011.

Cowi, Arup and Systra handled vibration analysis as well as all other design and engineering works. Trevi has been subcontracted to do ground engineering.

The TBMs are completing the drives in pairs and the first two launched in 2013 from Norrebro Runddel station site.

The first of four tunnel drives have completed, Arup announced earlier this year, saying, each travelled over 5.4km and installed a total of 7,090 segmental lining rings. "The TBMs have completed the project's first section of tunnelling marking a major milestone for the Cityringen project. From there, both TBMs will be transported over ground to the other side of the city to continue the excavation of the future metro tunnels."

The second pair has drives from the Kontrol-og vedligeholdelsescenter ('control and maintenance centre')

site, through a bifurcation executed with a small overland transfer. The machines will then be taken by road to Triangeln to commence the main drive back to meet the first (eastern) arm of the bifurcation. The total length of the project will be 15.5km with 17 underground stations, excluding the control and maintenance centre.

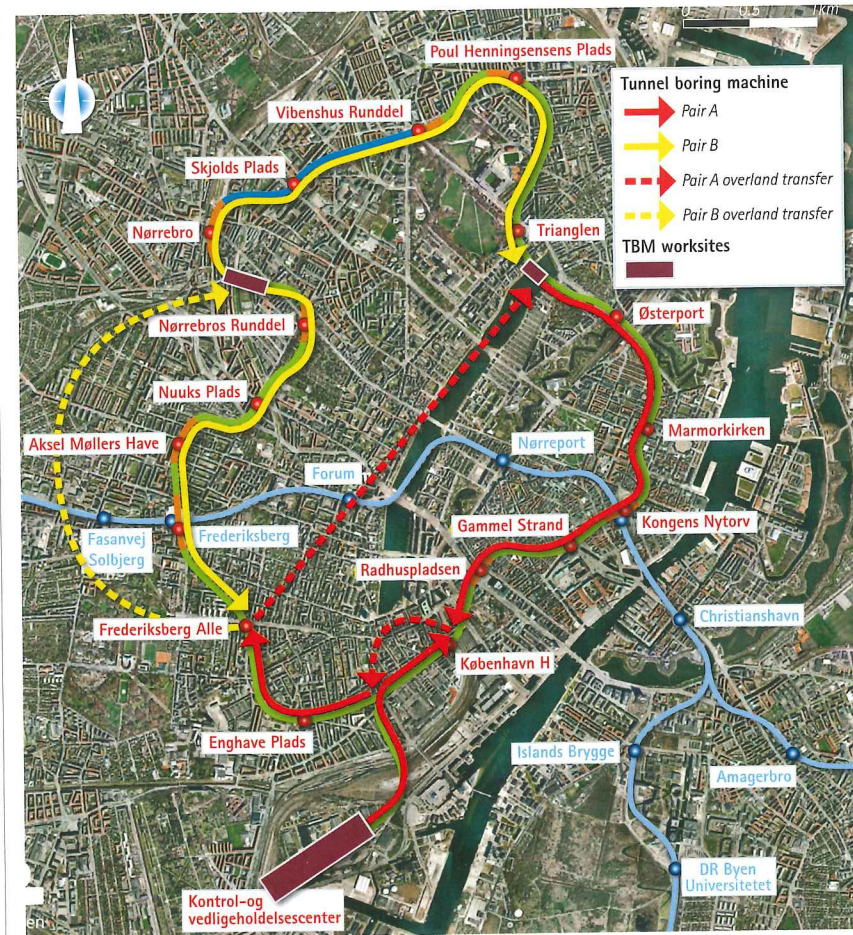
Metroselskabet is also launching a new branch of the metro off towards the city's northern port, called the Nordhavn Branch Line. Hochtief, together with Züblin, signed a EUR 150M (USD 203.15M) contract with Metroselskabet for the, the company announced on June 11, 2014.

In addition to construction of a total of more than 3.5km of tunnel, the project also comprises the turnkey delivery of the Nordhavn subway station. To this end, the joint venture which consists of HOCHTIEF Infrastructure Nordic branch and Züblin A/S will mine two approximately 1,800m- and 1,600m-long tunnels TBM. Beside the roughly 80m-long Nordhavn subway station, the joint venture will also construct a small tunnel and a ramp structure, a service shaft/emergency exit and a pedestrian transfer tunnel to the adjacent, already existing S-train urban rail station Nordhavn. There are no settlement or damage criteria, and the risk is on the JV. Pre-investigation had been done with a three-stage building assessment.

"Some of the older buildings are built on timber piles," says Soren Eskesen, head of Cityringen tunnelling for the client. "We must not lower the groundwater around these areas - if these wooden piles are exposed to air, they will [drastically] deteriorate. Hence the choice of a closed face TBM.

"We also require 90 per cent water infiltration during station construction. Retaining walls stretch down well below the foundation level, with the deepest reaching down to 45m and the shallowest to 25m"

Below: Alignment map of the Copenhagen Cityringen project



# PARALLEL LINES

To improve service in Paris' Metro Line 13, two tunnelling contracts awarded this year will add 6km to Paris' Metro Line 14

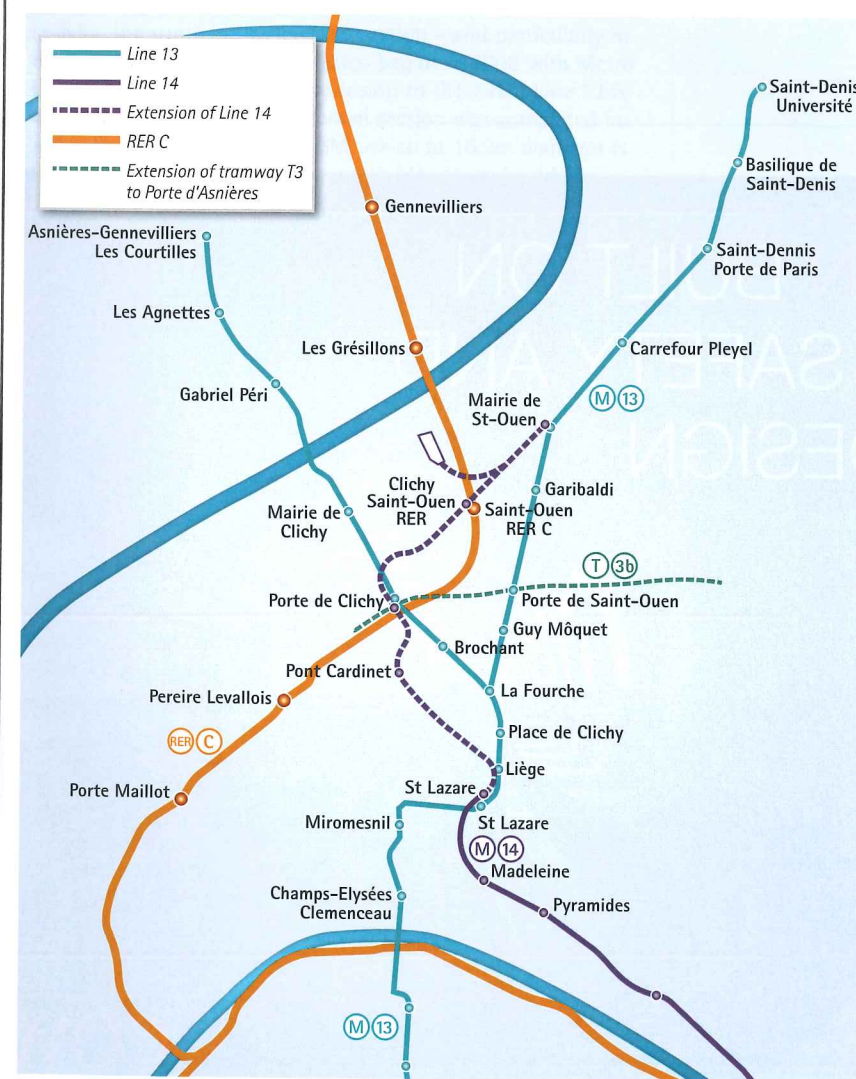
PARIS METRO'S Line 13 is overloaded, with more than 600,000 passengers a day. In the northern part of the line alone, 15 cities are served and that translates to about 400,000 inhabitants and 620,000 jobs as well as a university.

The state-owned public transport operator RATP (in French Régie Autonome des Transports Parisiens) has short-term solutions, such as increasing the frequency of trains, improving station platforms and adding bus routes. It has also been working on a long-term solution, which involves an extension to Paris Metro's Line 14, which would reduce the number of passengers on Line 13 by as much as 25 per cent, according to projections.

Completely underground, there are 5.8km of tunnels to be built in two packages, and four new stations. There will be two new interchanges with Line 13.

On March 17, 2014, RATP announced that it had chosen a consortium of companies led by Eiffage Travaux Publics with Razel-Bec to build the first section of the Line 14 extension.

Below: Line map for the Paris Metro



Lot 1 concerns the section between Saint-Lazare and Porte de Clichy, and includes a 3,600m-tunnel and two underground stations (Pont Cardinet and Porte de Clichy).

The contract is worth EUR 220M (USD M). Deep foundations of the Pont Cardinet station have been assigned to SEFI-INTRAFOR Group subsidiary FAYAT.

In July 2014 a consortium consisting of Bouygues Travaux Publics (lead company and a subsidiary of Bouygues Construction), Soletanche Bachy France, Soletanche Bachy Tunnels and CSM Bessac signed a contract worth EUR 164.9M (USD 182.25) with RATP for the second tunnel package of the Paris metro line 14 extension project, north of Paris, running from Clichy-St Ouen to Pleyel, in the neighbouring town of St Denis.

Lot 2 includes a 2.2km-long tunnel linking Clichy-St Ouen and Pleyel, including a tunnel that links to the train maintenance and marshalling zone; the Mairie de St Ouen station; four ancillary structures, including reinforcing the infrastructures of line C of the RER (Regional Express Network).

Bouygues says the tunnel drive will be carried out with an 80m-long EPBM, and includes several major technical challenges, such as taking account of the diversity of soils along the route of the tunnel and the reinforcement of the infrastructures of line C of the RER, beneath which the connecting tunnel to the train maintenance and marshalling zone will pass.

"To meet these challenges, the consortium will analyse all the data collected from the TBM and resulting from monitoring on the surface in real time in order to have the capacity for immediate response."

Bouygues Travaux Publics and the entities of the Soletanche Bachy group have previously carried out several underground infrastructure projects: a section of the Toulouse metro and the second tube of the Toulon tunnel.

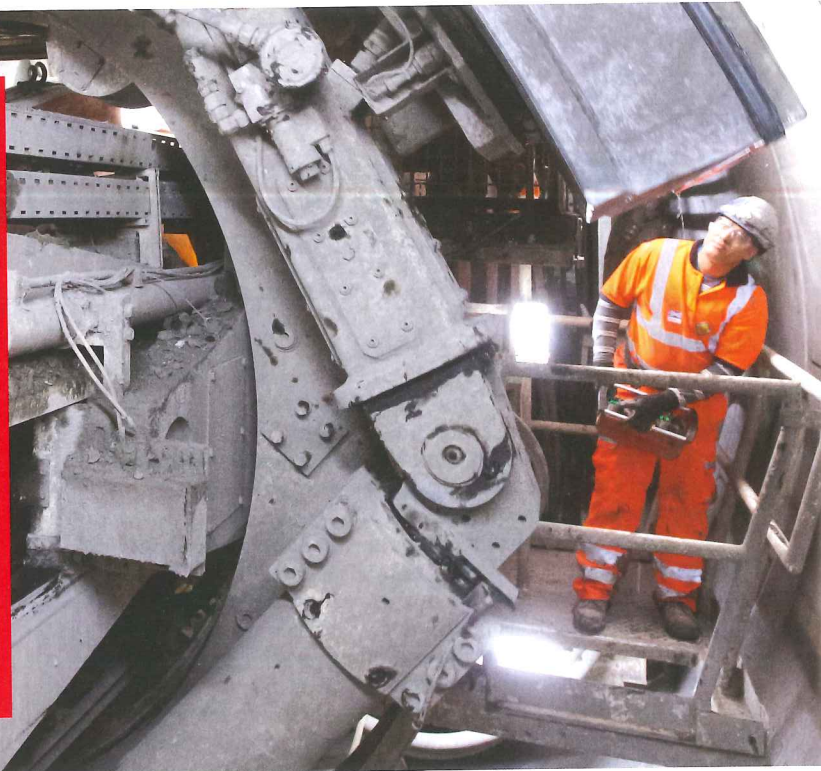
Work is expected to be completed at the latest by 2018.

Further extensions are planned on this line which, by 2027, will link Saint-Denis Pleyel in the north of Paris to Orly airport in the south

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# LATIN AMERICA OVERVIEW

Major metro projects across Latin America are driving tunnelling demand and testing the capabilities of contractors, designers, and operators. Brazil and Panama are covered directly in this section of the World Metros Supplement, but in this article we give a roundup of other works in the region

**I**N GLOBAL terms, while Latin America's 6.7 per cent market share of tunnelling activity is still dwarfed by that of Asia-Pacific, which accounts for a mighty 48.7 per cent, the industry is gaining real traction in many countries.

### MEXICO

Probably the biggest infrastructure project for the SCT is the proposed new Mexico City "mega-airport", which was announced last September. Weighing in at USD 12bn, the 550,000m<sup>2</sup> airport, designed by Foster & Partners, won't actually feature any passenger foot or train tunnels but the entire structure will be serviced from below.

After a gap of about 20 years when there was little or no activity, the surge in tunnel construction – and particularly in mechanised tunnelling – in Mexico began in 2008 with Metro Line 12 in Mexico City. The extension to the 24km Line 12 is ongoing, although the 7km tunnel section was completed in 2012. Robbins supplied the TBM, which at 10.2m diameter is the largest ever to have been used in Mexico and work was completed very quickly, says Gonzalez. And, in fact, the tunnel section is the only part of Metro 12 that is currently open. Gonzalez reports that the Spanish manufactured trains have proved to be incompatible with the rails.

"The trains work in the tunnels because they don't have such sharp turns, but the rest of it is closed. It's a mess and there are some other metro projects [planned] but with this scandal everything has been stopped."

Having said that, however, Guadalajara is apparently considering building its first underground metro line. If it goes ahead it will pass under the city, including beneath the historic colonial area.

Projects are coming thick and fast from both the current administration, which was elected in 2013, and from private/public joint ventures and confidence is high, particularly when it comes to mechanised tunnelling. Amitos, the Mexican Tunnelling Association has promoted the method and run courses on it.

A downside to the increase in activity in the country, he added, is competition from large international companies wanting a piece of the action. "Local contractors have to be more competitive and try to find a way to win bids," he said.

### COLOMBIA

Improvements to the urban infrastructure in the future may include an underground subway system in Bogota. A 24km long subway line is under consideration, along with its second phase expansion up to 76km.

"There is a political appetite for big projects that can enhance Colombia's economy and tunnels are usually included within those projects," says Santiago Gutiérrez Ruiz, project manager at Ingetec.

**Right: TBM factory acceptance for the Fortaleza project**



### CHILE

With the recent boom in commodities, Chile's mining, energy and infrastructure sectors have seen significant investment, including in tunnels and underground projects, according to Alexandre Gomes, general manager at Geoconsult's Santiago location. Construction is ongoing on new lines for the Santiago Metro. The USD 3bn project to build Lines Three and Six will feature around 37km of underground works, with 28 underground tunnels.

### PERU

"The most important infrastructure project in the history of Peru," is how Vaca describes the USD 4bn Lima Metro project, the construction of which started last August in a ceremony attended by President Ollanta Humala. The metro will transform the city, sections of which will be turned into green spaces

# PANAMA METRO

Central America's first metro is a boon for tiny Panama's traffic-beleaguered highways, but despite a positive start, future work neglects tunnelling

**T**HE ISTHMUS of Panama is, for its size, one of the most influential geological structures in the world. It was formed by underwater volcanoes, a tectonically-induced rising of the seabed, and then gradual sedimentation and siltation of the result to create a more complete land bridge.

Recent scientific discoveries made during engineering works to expand the Panama Canal have pushed the date of its formation (in a tenuous state) back from a few million years, to around 10M years or even more. The visualisation of the state of this bridge between North and South America drives a lot of what scientists believe they understand about the Earth's current glacial cycles. The glaciation of the Arctic, and the creation of the Gulf Stream are thought to be caused by this slender link. It also allowed mass migration (the "Great American Interchange") of plant and animal life between the Americas.

In modern Panama, the eponymous capital city sits on the only practicable crossing at the narrowest part of the

country, and efficient movement of people through public transport is vitally important to keep the main highways as clear as possible. The country's economy has been relatively undamaged by the global financial crisis, with up to eight per cent annual growth, and public finances were available to be levelled at the problem of residents relying on buses and cars, a problem that "would cause the collapse of vehicle traffic by 2015" according to the Panama Ministry of Economics.

## BURYING YOUR PROBLEMS

The solution to the traffic jams of Panama City was metro. And the City awarded the USD 1.45bn contract (which rose to USD 2bn with addendums) to construct Panama Metro Line One in 2010 to an Odebrecht-FCC consortium. The scope of the underground works was 7km of tunnels and seven underground stations, with the remainder of the 13.7km line to be constructed on viaducts with five elevated stations. Although it is a dream, and was a pet project of former Panamanian president Ricardo Martinelli to set the ball rolling to have an entire underground transport system for the city by 2035.

## CRITICAL TUNNELLING THROUGH DIFFICULT GEOLOGY

According to Santiago Erans, Panama Metro Line One leader for FCC, The critical element for the success of the project was the tunnelled stretch of the works. Some 7.3km (a 4.2km

Below: An elevated section of the metro



Table 1. Tunnel overview

Name	Value
Total length	7.3 Km
Length of first drive	4.2 Km
Length of second drive	3.1 Km
Quantity of rings	4,075 u
Quantity of segments	28,525 u
Excavated diameter	9.77m
Internal diameter	8.7m
Maximum gradient	3.5 per cent

Source: FCC

and a 3.1km drive) of tunnel were excavated using two 9.77m by Herrenknecht EPBMs through difficult geotechnical conditions.

Rock up to 100MPa was encountered in places, and the highly fractured nature of the ground meant that the TBMs "needed their tools changing into hyperbaric form" according to Erans. In general, excavation took place in problematic areas with mixed geology, fractures and shallow ground with a changing level of rocky substratum. A general overview of geology was provided by the client during the tender process, allowing an analysis of the information to give an idea of the hydrological and geotechnical situation along the drive, a complementary study was undertaken.

Erans continues, "The complementary study expanded the stratigraphic, tectonic and hydrogeological knowledge of the terrain as well as the geotechnical characterisation of the terrain, allowing geotechnical parameters to be determined for tunnel design, stations and shafts.

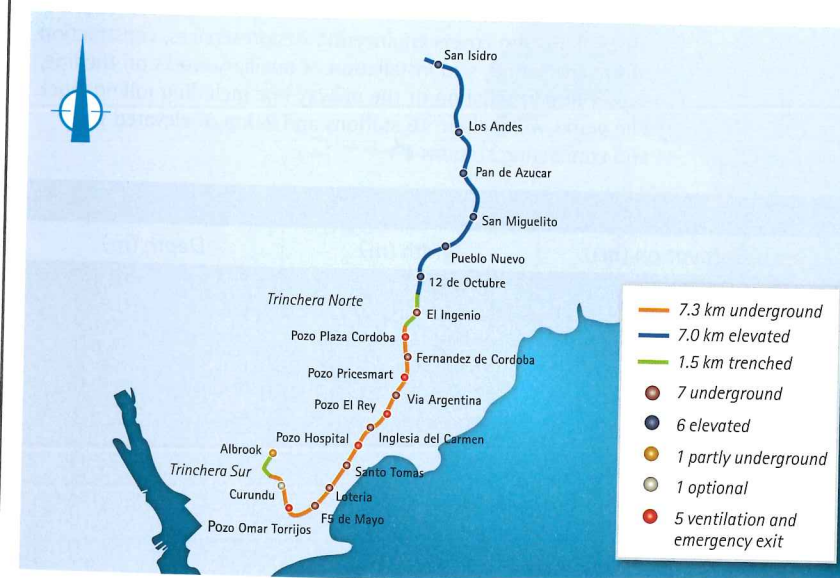
"Passive seismic refraction (micro tremor) and electric tomography determined the rock and soil contact boundaries. In addition, based on the speed of the waves, the modules of dynamic deformability of rock and soil and their behaviour faced with seismic actions and the excavation possibilities could be determined. All of this allowed us to accurately define lithological distribution and complete a geotechnical and hydrological characterisation of the terrain, especially relative to its deformability, abrasiveness of the rocks and the aquifer definition and parameters of hydraulic loads."

In total 58 explorations were undertaken (34 in tunnels



Above: Work ongoing in a congested site

Below: Route map for the Panama Metro



and 24 in stations) that covered 1856m (approximately 392m in soil and 1464m in rock). In addition 165 permeability tests were carried out and 234 pressure tests. Three shafts were set up in the station areas (with a total of 75m of perforation) for pumping tests. In terms of geophysical works, 2300m of passive seismic tests were carried out, split into 27 types, and a tomographic electric test of 400m.

With regards laboratory testing, mechanical and deformation classification and state tests were carried out which included uniaxial compression, uniaxial compression with extensometric bands, triaxials for rock and soil and traction resistance.

For the pump tests a diameter perforation test was carried out allowing a tube of 200mm minimum ventilation diameter to be positioned. Each pump shaft had at least four piezometrics.

## LINING

Universal precast concrete segmental rings lined the tunnel and were grouted with a two component grout to achieve uniform contact and minimise movements and achieve uniform pressure, and to help reduce permeability. Segments were 1.6m-long

and 350mm thick, and were in a 6 + key arrangement.

**CRITICAL PATH CHALLENGES**

Erans said the team knew it would be difficult to deliver the whole project in 38 months, and points out that this included all design, enabling works, auxiliary line and M&E installation, and rolling stock supply. "Right from the start we analysed in detail the activities which formed part of the project's critical path and we studied the possibility of reducing, within what was possible, the length of some parts of the process, guaranteeing the delivery of the tasks without the possibility of delays."

There were several key decisions. "Firstly, from the detailed analysis we did we concluded that the TBM purchasing process needed to start on day one. This included a specialised team overseeing the whole process at each stage. This team had to focus on the TBM fabrication in Germany. It was also critical to properly select the team responsible for affected utilities. Several companies were contracted to detect and organise the re-locating of utilities affected by the project.

"Then the construction process for the elevated stations was changed, making it independent from the lines. This way the lines could continue to be worked on without the stations having been finished, and in addition certain parts of the design were changed, so that instead in situ construction, they were built with prefabricated elements. The goal throughout these changes was to reduce the construction time.

Erans adds that during the project, the team had to take measures to bring the project back on schedule when unforeseen complications slowed them down. "For example, we increased the number of hydromill trench cutters from three to four to accelerate the excavation of the concrete walls on the underground stations; we also increased the amount of formwork on elevated stations, and finally

**Box Metro timeline**

- October 2009 – Pöyry, Cal y Mayor and Geoconsult selected to provide consultancy services and conceptual design on Line One
- January 2010 – Panama Government invites pre-qualification tenders seeking interest in design and build of Line One
- August 2010 – Bids for design & build submitted by Linea Uno Consortium (Odebrecht&FCC)
- October 2010 – Linea Uno Consortium selected to build the metro
- December 2010 – Work commences on metro
- August 2011 – FCC takes delivery of two TBM's built by German company Herrenknecht AG, shipped to arrive separately in Panama in September and October
- September 2013 – Construction 92% complete allowing first test-run of rolling stock
- February 2014 – Completion of construction
- April 2014 – Inauguration of metro

we increased the number of machines used in the piling of the underground station accesses and the trenches (the transition sections between tunnel and surface)."

On particular challenges working in Central America, Erans says: "Sourcing staff and equipment for a project of this scale in Panama was a challenge. Local engineering expertise in Panama was lacking due to no previous experience on projects of this type or scale. Careful management and planning allowed the consortium to source their workforce for the project (90 per cent Panamanians) and complete the design, shipping and assembly of the two TBMs and vital materials in just 14 months."

**FUTURE**

The metro is required to transport 15,000 people an hour now it is in operation. When all four lines and a tram system are completed in 2035, as per the 'Red Master Panama Metro Plan', it is expected to transport 40,000 people an hour. Erans concluded, "The opening to the public in April 2014 marked a significant moment in Panama's economic and urban development and represented a shift in attitudes towards public transport investment in Central America. The Panama metro is the first system of its kind in the region."

Continuing the government's USD 15bn programme to upgrade Panama's infrastructure, the same consortium of Norberto Odebrecht and FCC was awarded the contract for Panama Metro Line Two on 14 May 2015.

However, this section for the east of the city is not underground. The bid of USD 1.858bn against a reference price of USD 1.819bn covers engineering design services, construction of the civil works, and installation of auxiliary works on the line, supply and installation of the railway line including rolling stock. The works will include 16 stations and 21km of elevated track and connecting stations

Table 2. Underground stations for Line One

Station	Length	Excavation (m3)	Width (m)	Depth (m)
5 de Mayo	115.00	46.680,00	19.20	22.50
Lotería	100.00	40.281,60	19.20	20.98
Santo Tomas	115.00	48.664,32	19.20	22.04
Iglesia del Carmen	115.00	48.645,32	21.15	20.00
Visa Argentina	115.00	53.776,88	21.50	21.75
Fernandez de Cordoba	115.00	42.444,86	17.60	20.88
Ingenio	115.00	31.682,59	14.50	19.00

Source: FCC

# REALISING RIO

Cutting under the dense urban environment of Rio de Janeiro's southern and western sprawl is calling for a mix of measures, from drill and blast with shotcrete lining, to segmentally lined TBM drives. The mixed ground showed its complexity with the emergence of a sinkhole in 2014, but careful monitoring and a quick response is keeping the project on track for the 2016 Olympic Games

**Key statistics**

- Project Type: Metro upgrade
- Scheduled Completion of Upgrade: 2015
- Estimated Cost of current works: USD 1.31bn
- Location: Rio de Janeiro
- Opened: 1979
- Metro Length: 42km
- Operator: Rio Trilhos

AS WELL as improvement works on Line One of the project, engineers are, at the time of writing, working towards completion of the 16km Line Four.

Lúcio Silvestre, contract director of the building consortium Consórcio Construtor Rio Barra, responsible for the construction of Line 4 connecting Barra da Tijuca and Gávea says: "This is a highly complex construction project with cutting edge engineering solutions.

"The main challenge has been to develop geotechnical models for underground works, while combining logistics and community relations, so as to avoid inconvenience in the daily

life and routine of the surrounding population."

**DIFFERENT METHODS**

Tunnels of Rio de Janeiro Subway Line 4 are built using two different construction methods: NATM and TBM. The subway will cover 16km from Barra da Tijuca in the west portion of the city, to Ipanema in the south

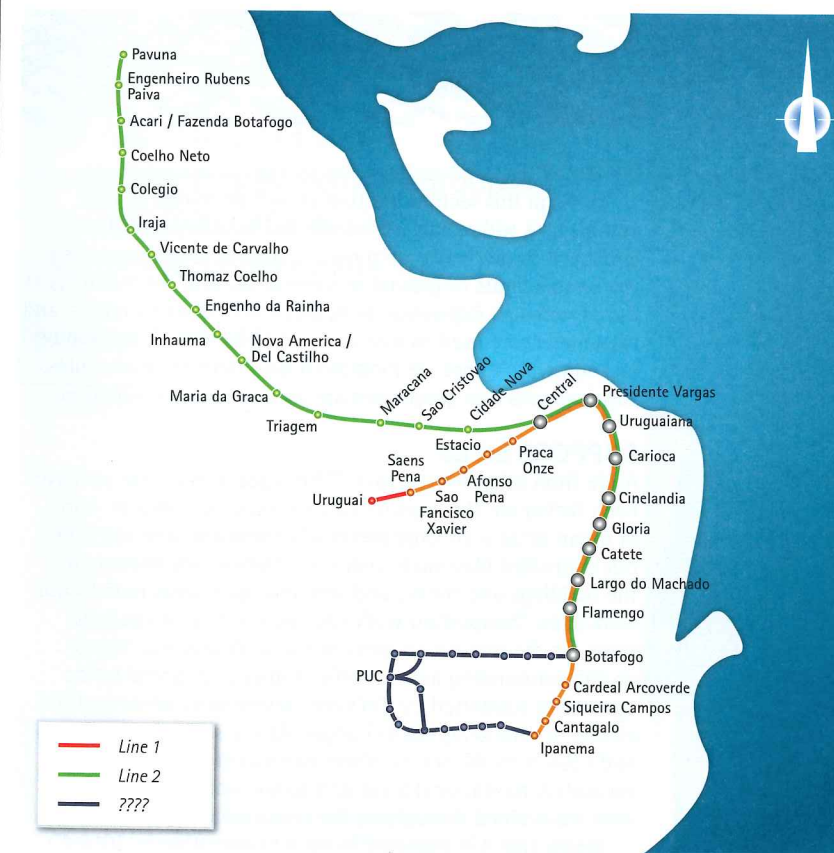
Started in June 2010 in the western neighborhood Barra da Tijuca, the tunnel boring operations by June this year had covered more than 8,000m between Barra and Gávea. Over this stretch, the boring operations are carried out using NATM -- drill and blast, with controlled blasting. This method is suitable for rock boring, and consists of lining walls and arches with rock bolts, wire mesh and shotcrete, advancing while controlling deformation.

On a daily basis, blasting is monitored by seismographs to control vibrations and monitor noises and building settlements, in addition to instrumentation and previous assessments of the surrounding buildings.

This method was employed in the largest rock-excavated twin-tunnel connecting subway stations in the world, covering a stretch longer than 5km, from Barra da Tijuca to São Conrado.

From Gávea to Ipanema, the tunnel is being bored by TBM, with 2,700t, 120m

Below: Route map of the Rio de Janeiro Metro



### Sinkhole

In the early hours of 11 May 2014, two sinkholes appeared on Rua Barão da Torre in Ipanema, where the TBM was excavating. Vidigal explains, "The outcome of the analyses of soil settlement that occurred in the morning of May 11 at Rua Barão da Torre in Ipanema shows that the incident was caused by an abnormal and specific behavior in the fractured rock face during the excavation of the subway tunnel in that street. The rock was dismantled and affected small neighbouring blocks, thus causing decompression of the soil. The process then evolved up to an area of sandy soil, and on to the surface."

The study also shows that four factors were at play in limiting the impact of incident: the excavation method, pretreatment of soil, monitoring of the ground and surrounding buildings' stability, and the prompt and efficient deployment of the Contingency and Emergency Plan.

"As soon as the first gap on the surface was found, the area was blocked off, excavations were suspended and it was found that there was no risk to the foundations of the surrounding buildings, as it was a localised incident. Once the area was blocked off, water and gas services were stopped and the holes were filled with concrete."

In a construction project of this size, the buildings surrounding the excavation of tunnels and stations are permanently monitored. The buildings receive instruments (settling pins and inclinometers) to monitor how buildings behave before and during construction works. The results from these instruments are within the expected limits and the buildings are not at risk."

The project maintains that the use of TBM is the "most suitable and safe piece of equipment for tunnelling the subway that will connect Ipanema and Gávea."

in length and 11.5m in diameter.

The TBM is building subway tunnels between the stations General Osório (Ipanema) and Gávea, causing a smaller impact on the surface areas. This construction method is best suited to the geology of Rio's south portion, consisting of sand, rock and water.

### MANAGING INCONVENIENCE

Projects in densely populated areas often face two major challenges. First, how to undertake a major construction project without bringing the city to a standstill by flooding the streets with site equipment and materials movements. Second, and a challenge particularly difficult for Line 4, how to minimise the impact on surrounding buildings.

The Rocinha favela, a 1940s and 50s slum now home to some 70,000 inhabitants in an area of just 1.43km<sup>2</sup>, occupies an area of hills and valleys directly above center of the tunnel route.

The houses are poorly constructed and as high as eight stories in some parts. A landslide in 2010 warned engineers of the weakness of the geology to be cut through. The lack of sewerage systems has further weakened



**Above:** Segment storage yard and gantry crane

**Below:** Waterproofing applied to the cavern walls



the 8m of fractured rock and up to 15m of soil cover.

Through this section the tunnels will be mined by drill and blast. A wide range of monitoring solutions have been employed to give early warning of blast vibrations breaching the 6mm/s limits or ground movement putting the buildings at risk of damage. Repression pins, piezometers, seismometers and tassometers are used to monitor at the moment of detonation and some 50 homes are monitored daily with repression pins. Seismographs and geophones are used to monitor vibration.

### SUPPORT SITES

Aside from this, Silvestre says, "The biggest challenge we have been facing are the logistics conditions, as we need to work in urban areas with large pieces of equipment, and carrying out controlled blasting in order to minimise any impacts to the buildings and traffic, and very few open areas next to our work sites. "Supporting work sites were set up at strategic spots for the smooth progress of the work and less impact on the surrounding areas. Traffic studies and special traffic operations supported by Rio's city government minimised the effects of temporary road changes. At the squares of Ipanema and Leblon, in the south, where two subway stations are excavated, recreational areas and senior workout facilities were maintained throughout the construction period."

Metro Line 4 is expected to go into operation in 2016

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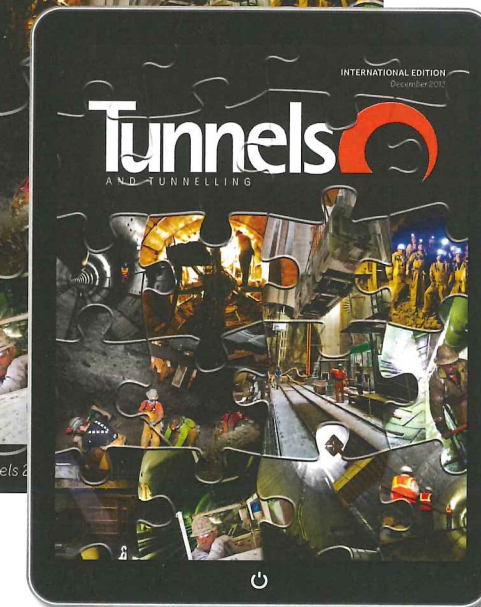
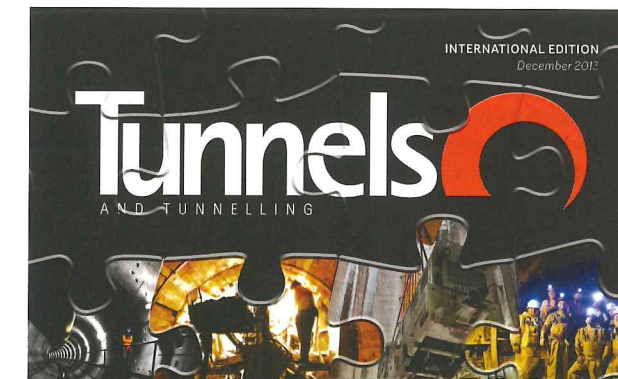
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# MIDDLE EAST OVERVIEW

INVESTMENT IN large infrastructure projects and strategies for economic diversification are driving demand for tunnelling in the Middle East.

"These countries want to be regional hubs for industry and commerce, not just oil and gas, and to do that you have to have cities where people can live," said Nick Chittenden, BASF's regional manager – Middle East, Egypt and East Africa – for underground construction.

The pace of tunnelling development has been very fast, growing from the first tunnels built for the Dubai metro about 10 years ago.

This trend is illustrated by figures from business analyst Timetric. In 2013 the Middle Eastern tunnelling and drilling equipment market was the smallest regional market, accounting for 3.2 per cent of the global market and with a value of USD 528.4m. Saudi Arabia was the largest market, with a 47.7 per cent share, followed by the UAE, Qatar and Bahrain with 47.2 per cent, 2.9 per cent and 2.1 per cent respectively. However, the region is forecast to achieve a compound annual growth rate of 10.76 per cent in the period 2013–2018.

The Middle East's importance to the tunnelling industry was recognised at this year's World Tunnelling Congress in Croatia where the Qatar Tunnelling Society was accepted into the ITA and it was announced that the UAE will host the WTC in 2018. The annual Arabian Tunnelling Conference and Exhibition, organised by the Society of Engineers – UAE in partnership with the ITA, has also become an established fixture on the industry calendar.

This year's event will be held in Dubai from 23 to 25 November.

In Dubai, Expo 2020 has been motivation for a 15km extension to the metro's Red Line from Nakheel Harbour & Tower Station to the expo site. The winning consortium is due to be announced in January next year.

In Qatar, the 2022 Fifa World Cup and National Vision 2030, the country's economic and social development plan, are contributing to construction industry growth. A big part of that is the USD 43bn Qatar Rail Integrated Network, which includes the USD 36bn Doha Metro, and the Lusail Light Rail Transit.

An impressive pipeline of work in the Middle East is available for contractors, although the challenges of working in a region with limited existing infrastructure are still being discovered

## OFF THE BEATEN TRACK

Elsewhere in the Middle East, metros are providing work, or potentially fertile contracts, for the tunnelling industry.

Tunnelling is also under way on the USD 22.5bn metro in the Saudi Arabian capital Riyadh.

Here seven TBMs will excavate around 35km of tunnels for the 178km transport system. The tunnels for the six-line metro are 30m deep.

The design and construction contracts have been awarded to three consortiums – BACS (Blue and Green lines); ANM (Red line); and FAST Orange, Yellow and Purple lines) – and the project is expected to be completed by 2018.

In Egypt, a joint venture led by Vinci Construction Grands Projets with Bouygues Travaux Publics, a subsidiary of Bouygues Construction, has won a USD 300M contract to build the extension of Line 3 of the Cairo metro.

The project comprises Phase 4 of the transport system, continuing on from Phase 2, and involves construction of a 5.15km tunnel and five underground stations on the east-west line between Haroun and El Nozha stations.

A metro is proposed for the Jordanian capital Amman as part of the city's 2025 Vision, while Kuwait City also has plans for a metro to help ease the worsening traffic congestion. The USD 7bn transport system will comprise four lines and 60km of the 171km will be underground. The project is part of a USD 25bn rail network linking Kuwait with its five partners in the Gulf Co-operation Council – Saudi Arabia, Qatar, Bahrain, Oman and the UAE.

Tehran's metro network is also earmarked for expansion and in Saudi Arabia bidding is expected to open later this year for construction of a metro rail system in Jeddah.

In the holy city of Mecca, which currently has no public transport system, a 188km metro network with 88 stations on four lanes will cater for the city's 1.6 million permanent population and the nine million Haj and Umrah pilgrims who visit each year.

Work on phase one will start next year and the network is due to open in 2019.

In Madinah, the three-line metro will comprise 71 stations and 92km of railway – around 25km underground. Before the system opens in 2020, engineers face the challenge of tunnelling through lava, as Madinah sits beside the Harrat Rahat lava plain, the largest volcanic field in Saudi Arabia.

Nick Chittenden believes that although the pace of new tunnelling projects will eventually slow, activity will continue in the Middle East for the next 10–15 years, and much of that will be sustained by Saudi Arabia, which has plans for several new metros

# DOHA'S DESTINY

The 'project of the hour' for the tunnelling industry calls for an impressive 21 TBMs from manufacturer Herrenknecht to deal with the limestone bedrock (and shale layer), which calls for a degree of flexibility

IN QATAR, the 2022 Fifa World Cup and National Vision 2030, the country's economic and social development plan, are contributing to construction industry growth which, according to the Construction Intelligence Center, is expected to reach a record 13.28 per cent during the period 2014–2018.

A big part of that is the USD 43bn Qatar Rail Integrated Network, which includes the USD 36bn Doha Metro, the Long Distance Passenger and Freight Rail, and the Lusail Light Rail Transit. The metro comprises three lines – Red, Green and Gold – which are being built simultaneously and by the start of the second quarter this year, 21 no. 7m-diameter EPBs from Herrenknecht had been commissioned to excavate the soft ground and rock underneath the Qatari capital. So far four EPBs are dedicated to the 11.3km of twin tunnelling required for the Red Line North and five for the 12.05km of the Red Line South which is underground. Tunnelling will be at an average depth of 20m. This 40km line, which extends from Al Wakra in the south to Lusail in the north, will have 12 underground stations, five stations elevated at grade.

A milestone was reached on the Red Line in April when, for the first time on the metro project, one TBM was lifted from one station site to another. Al Khor TBM, which had finished its first stretch, from Al Qassar station to Doha Exhibition &

## Key statistics

- Name Doha Metro
- Location Doha, Qatar
- Length 300km
- Number of Lines Four
- Number of Stations 98
- Estimated Cost USD 36bn (approximately)
- Conceptual Design Consultants Qatari Diar and Deutsche Bahn

Convention Center station, was conveyed back to Al Qassar for relaunching towards the north of Doha, to complete the tunnelling section between Al Qassar, Katara and Legtaifiya.

Two joint ventures have been selected as design and build contractors for the Red Line – one led by Impreglio, South Korea's SAK Engineering and Construction and Galfar Al Misnad; and the other led by Qatari Diar Vinci Construction, GS Engineering and Construction and Al Darwish.

The Green Line (Education Line), being built by the joint venture of Porr Bau GmbH, Saudi Binladin Group and Hamad Bin Khalid Contracting, extends from Msheireb Station in the east to Doha West International. Here, six EPBs are working on the 16.6km, seven-station stretch between Msheireb and Education City, again at a 20m depth.

Six EPBs are also currently working on the 13.3km of tunnelling for the Gold Line, a contract awarded to the ALYSJ joint venture comprising Greece's AKTOR, the joint venture leader; India's Larsen and Toubro; Turkey's Yapi Merkezi and Sezai Turkes Feyzi Akkaya Marine Construction (STFA); and Qatar's Al Jaber Engineering. Atkins is the lead designer. The Gold Line, which extends from Ras Bu Abboud Station in the east to Sport City in the west, will consist of 10 underground stations.

Precast segments will provide the final lining for the Gold Line and the TBM tunnels will be connected to emergency escape passages excavated using NATM methods. Excavating the stations has also had its challenges.

"In this case the pumped water coming from the excavated pits cannot be easily discharged to Doha's central sewage system so a special method of deep reinjection wells has been implemented," says Kontothanassis

Below: Route plan for the Doha Metro project



# ASIA OVERVIEW

The rising power in the global tunnelling industry is catching up and in some cases overtaking the metro networks of the Western World

**W**HILE ELSEWHERE in the world there is the occasional metro project in each region, Asia is littered with them. It is difficult to pick out individual schemes from the mass due to the sheer amount of development.

Looking at India for example, every major city has a large-scale metro project. The Delhi Metro, serving a congested city of nearly 20 million inhabitants boasts a daily ridership of over two million. The project is entirely utilitarian, and goes underground only when a practical above-ground solution is impossible. The 25.1km Line 1 opened in 2002, largely above ground this was the 'easy route', and since then more and more tunnelling has been required. The current network runs for over 200km.

As well as Delhi there is Kolkata (28km), Mumbai (11.4km), Jaipur (10km), Chennai (10km operational, 45km due), and Bangalore (20km operational, 114.39km planned) among others.

## CITY STATES

Moving to Singapore, the move to mass rapid transit has been a powerful one. Government has implemented large-scale works with amazing efficiency and speed. An incredible fee for owning cars to discourage traffic, as well as a rapidly growing public transport system, is a real 'carrot and stick' approach to driving demand.

Now completed projects such as the 40km Circle Line, and the initial stages of the Downtown Line have given way to later Downtown Line projects (total length 40km) and the new 30km Thomson Line project, with its East Line expansion.

Hong Kong, always a rival to Singapore as another island state (although with the muscle of China behind it), has had a section of rail for a century, which is undergoing refurbishment to keep it in line with modern standards. In the early 2000s, early design work began on WIL and SIL (the West and South Island Lines) as well as the Shatin to Central Link and Kwun Tong Line extension. A number of future projects are lined up, although some have a long timeframe to consider.



Above: Break through on the CC-07 contract of Delhi Metro

Taking the rail network as whole, it is over 200km long and has some five million riders per day.

## RISING SUN

Japanese foreign investment funds are key for the realisation of a number of metro projects in the Asia Pacific, but domestically metro work is weak. The demand is there, with Tokyo's last line opened nearly 10 years ago, and employees famously stationed to push passengers into overcrowded trains.

More recent work has focused on circular road projects around the city, as well as maglev routes around the country.

## WOKEN GIANT

Chinese cities with metro projects in planning and under construction include: Zhengzhou, Wuhan, Suzhou, Xiamen, Lanzhou, Nantong, Jinan, Nanning, Hohhot, Nanchang, Urumqi, Chengdu, Shenzhen, Foshan, Shanghai, Qingdao, Tianjin, Beijing, Fuzhou, Daxing, Xinhuang.

"The metros of China form the backbone of public transport," Mott MacDonald's managing director of China Paul Jenkins previously told Tunnels and Tunnelling. "There is a limited supply of cars permitted, which puts pressure on the metros - and quite rightly. In Beijing, for example, there is a lottery on who gets a car. The significance of this for tunnelling is that lines that opened two years ago in Beijing are already at capacity"

# DELHI METRO

With a metropolitan population of over 16 million, a failed foray into privatised bus services and cars choking up one of the densest road networks in India, need for further metro expansion in Delhi has never been more pronounced

**P**HASE ONE of the Delhi Metro kicked off in 1998 with the least tunnelling of all the phases. Some 13km of the 65km, three-line central Delhi network were underground.

Project developer Delhi Metro Rail Corporation [DMRC] estimates the cost of this portion at INR 105.7bn (USD 1.95bn).

The decision to go underground is not the first choice for Delhi, and it is a decision entirely based on cost. The price of an elevated line is roughly 10 per cent that of a tunnelled line, so if the government is in a position to acquire land along the alignment, it prefers to go over it.

Per kilometer, Delhi Metro tunnels costed around INR 2.5bn (USD 46M), while elevated line sets DMRC back some INR 250M (USD 4.6M) in 2012.

Completed in December 2005 just about three years ahead of schedule and on budget, Businessweek reported at the time that the achievement was a miracle in a country previously renowned for inefficient public works. Like many others, its praise for the miracle project fell on DMRC's former director Elattuvalapil Sreedharan, a hero of India known as 'Metro Man'.

## PHASE TWO

Tunnels and Tunnelling reported the start of phase two tunnelling in 2008 with the lowering of two 6.54m-diameter Herrenknecht EPBMs. Some 14 machines were launched that year, with excavation due to be completed on all drives by or during 2009.

The 30 tunnel drives called for this record-breaking number of TBMs working in a single city. Of the 124km to be added to the metro in this phase, 35km were underground. Driven 16km by TBM and 2.8km by NATM. The 20 underground stations were constructed by cut and cover, twice as many as in phase one.

## PHASE THREE

For phase three, around 45km of underground lines will be built with 31 underground stations. DMRC spokesman Anuj Dayal says that this will be almost as much as the underground work from the previous two phases combined. For the first time, Delhi Metro lines will have to cross. Some 25 TBMs will be used on the project, the first two of which have already been lowered to work on the north-south Violet Line.

Dayal says the corporation will set up a centralised TBM control room for this phase. The facility will monitor the 'functioning' of the TBMs with GPS technology, enabling coordination of progress. Bidding for phase three will be over by the end of the year.

## CHALLENGES

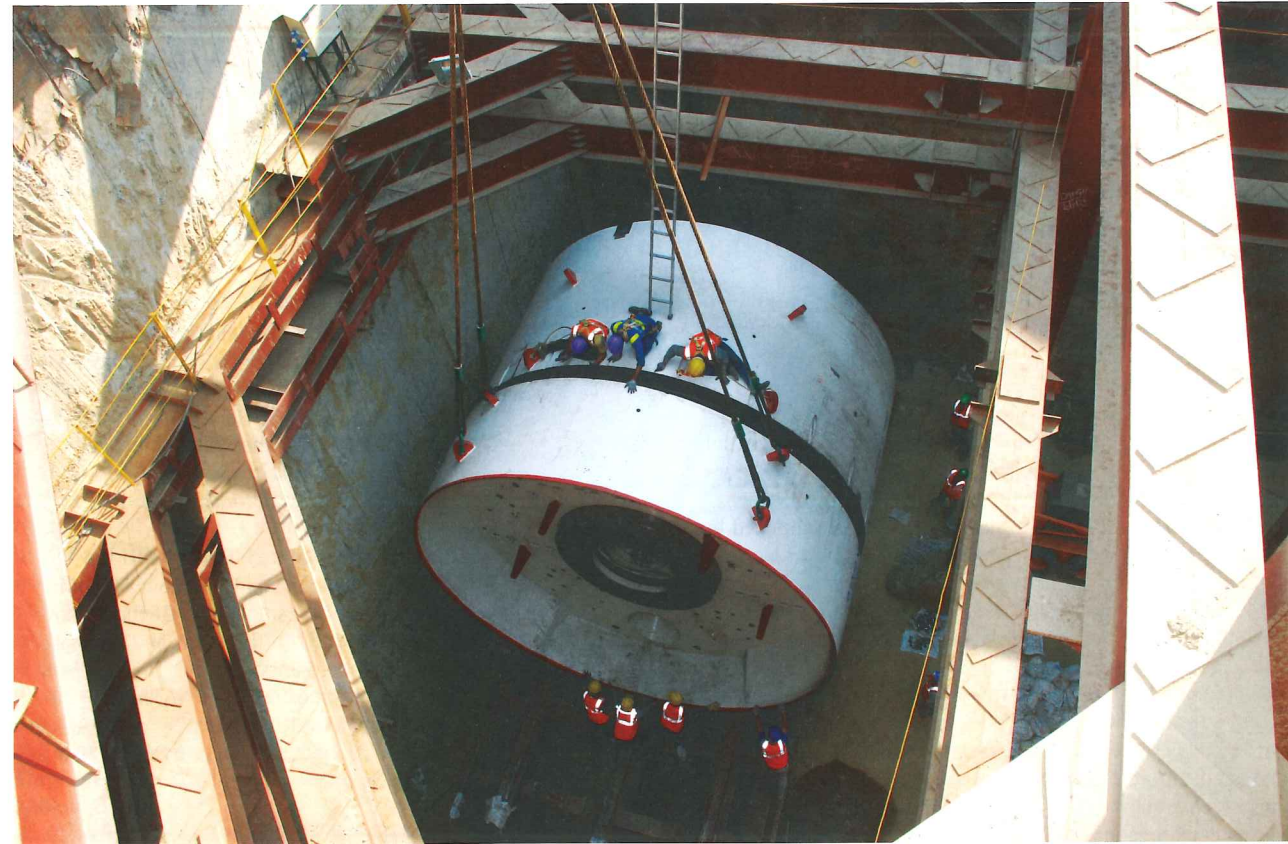
### Risk

One of the problems with doing business in India is the amount of risk being placed with the contractor. Mott MacDonald's Mohan Gupta says employers generally ask contractors to design all risk into the bid.

He says, "This is an issue as contractors often seem to face difficulties because of this and are not making very big profits in India. The client is not legally allowed to pay more [if circumstances change]. Professional understanding can [sometimes make

Below: The extensive metro system in India's capital





this] different, but I do not know of any cases to comment on.

"In the case of the Airport Express [section of Phase Two] I was only involved on the technical side, and so not overly affected [by the unexpected conditions]. Although with the balance of risk being entirely on the contractor, it is important that risk information is accurate and shared.

"I think the Airport Express was an example of lack of information at concept design and not intentional withholding of information," says Gupta."

He spoke to Tunnels and Tunnelling closer to the time, saying: "In most situations, preliminary designs have been

**Both: TBMs at different ends of the journey**

carried through to construction. On the Airport Express Line however, the client said alluvium soils reached down to around 30m, and the bid by the contractor was priced at that."

When digging began, it was found that the rock was higher than expected. Where the station was to be located, rock was 8m below the surface. Teams wasted two to three months on investigations and changing subcontractors and so on. Finally Airport Express contract C1 was delivered on time by the Alpine, Samsung and HCC JV with Mott MacDonald as designer. Bob Moncrieff of Rona Consulting previously told Tunnels and Tunnelling, "In India it is usual for all financial and geotechnical risk to be placed on the contractor and away from the client. They are very one-sided contracts. The industry is getting better at site investigation though, but with a short tender time, it is a brave contractor that undertakes extra investigation. I suspect if this does not change quickly, a contractor will eventually 'catch a cold' in unexpectedly bad conditions, and this will force prices up from then onwards. The current contract culture is short sighted."

**Land acquisition**

On some contracts, sites have needed to be set up before all land acquisition objections have been mollified. In one site visited by Tunnels and Tunnelling, an island of housing was fenced off in the middle of a bustling worksite preparing to construct a TBM reception pit.

Speaking to Indian Express recently, the new managing director of Delhi Metro Rail Corporation, Mangu Singh, said that previous land acquisition was undertaken through a now defunct Government Act, which required the invocation of an emergency clause. This was apparently nerve-wracking, as it was challenged many times, but the courts generally looked favourably upon what they saw as a vital infrastructure project.

Now, the Land Acquisition, Rehabilitation and Resettlement Act of 2013 has superseded the earlier legislation



# BANGKOK BEAST

Complex station works, and tunnel drives constrained by logistical and property issues are needed for the Blue Line metro extension in Thai capital Bangkok. Some of the stations are highly visible near the famous old parts of the city

**A** DECADE AFTER the opening of its first underground metro line, Bangkok is in the middle of a major upgrade to its public transport system. The first, Blue, line is being extended with both above ground elevated track and new tunnelled sections. A series of other lines are either in construction or being readied, to expand the city links over the next half a decade

"Most of the new lines are elevated" says Christian Schulz, an engineer with German consultancy firm Dorsch Consult who is currently on secondment as executive project director for the Blue Line works. "That is obviously less expensive than tunnel, though it can sometimes bring complications with land acquisition, utilities and traffic".

The city's first ever line, the privately developed BTS Skytrain, is an elevated system and has proved highly popular since it was completed at the turn of the century. Running through the busy tourist Sumkamvit area and down to the river it has not only helped alleviate the severe traffic congestion that used to bring the city to a near standstill at times but has stimulated retail and residential development. Some extensions are being added to this. An airport rail link is also popular.

The Blue Line, built by the government's Mass Rapid Transit Authority was the city's first underground line running in a horseshoe shaped loop north to south, finishing near the central rail station. Opened in 2004 it took a while to develop its ridership in a city with a large poorer population for whom ticket costs are difficult. But there is a growing middle class and it has become well used; it is also an important contributor to city development. As the deputy director for the Mass Rapid Transit Authority of Thailand, Peerayudh Singpatanakul puts it

"people are learning the habit of public transport".

The line will now be made into a complete circle, or rather an elliptical loop line, with the "missing" section completed up through the districts lying along the west bank of the Chao Phraya river. This section will be elevated, and so too will a 10.5km long westwards extension. But a 5.4km long connection across the river to the original underground at the south end will be in tunnel. There are four stations in this part, all underground.

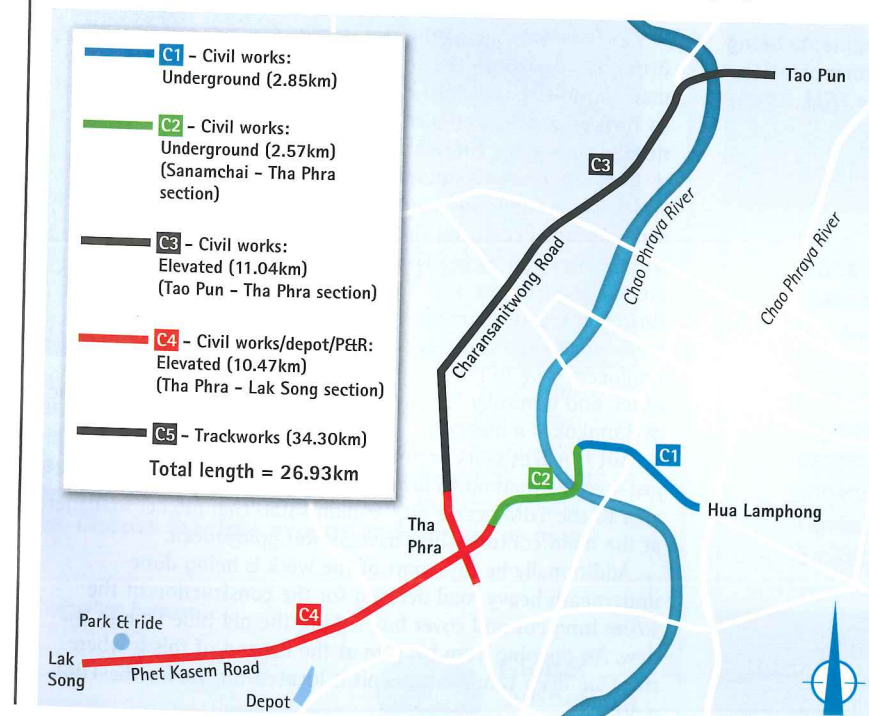
As well as going under the river, a key reason for tunnelling here is that the alignment passes through or nearby some of the oldest and culturally most important parts of the city, including alongside major temples and museums. These are part of the royal palace district and also significant as tourist sights. Towards the rail station end of the new tunnel it also runs underneath the Chinatown quarter, another bustling and important area. Elevated line would have been obtrusive.

"The new line is split into five major contracts," says Schulz "the elevated section to the north end, which is 11km long, the elevated western extension which also includes a depot works, trackworks, and then two tunnel contracts.

"The first of these is for a connection to the existing line at Hua Lamphong just outside the main railway station. A cut and cover excavation makes the link to the existing underground station and from there twin running tunnels are driven for 2.85km. There are two underground stations, the Wat Mangkon in Chinatown and the Wang Burapha closer to the old city."

The contract was let to ITD in February 2011 on a designbuild basis and is worth THB 11,441M (USD 381M) The other contract continues the tunnels for another 2.7km and also includes two underground stations, the Sanam Chai, situated just close to the Thai museum and nearby a temple with Bangkok's famous reclining Buddha, and then on the far side of the river, the Itsaraphrat. It concludes with a cut and cover section with an incline for the track making the

**Below: Route map of the project**





Above: Segments being transported to the TBM

transition to elevated way.

The tunnels themselves are twin bores of 6.44m diameter, which after installation of 300mm thick segmental linings and grouting, leaves running tunnels with an internal 5.7m. They are both using earth pressure balance tunnelling machines for the work, a Kawasaki for Ch Karnchang and a Terratec, for ITD on the first contract.

Both have to pass through the very soft clay layers which underlie the city and into water bearing sand layers beneath. Bangkok's geology is notoriously difficult for building construction, requiring major deep piling for most structures through the very soft clay layers - like toothpaste most engineers say - into the firmer sands and firmer clay layers under that. The city has also had issues in the past with water extractions from the aquifers beneath which caused significant settlement in the past, though it has slowed up following a ban on unregulated water use.

### STATIONS

Stations are conventional diaphragm wall box constructions, but relatively constrained by the narrow street pattern and the difficult property issues. These have caused some delays on particularly the first contract. For the ITD contract it also means double stacking the lines in the stations to keep the width down, with one of the stations deepened to 29m. First of the Ch Karnchang stations is also 29m deep.

The stations overall are 22m wide at the maximum point, with part of the station box, for concourses and escalator links, offset to one side and with a surface station building above that. It is the land purchases for the wider sections, which involve demolition of some buildings alongside the alignment which have held up some work.

The tunnels themselves are kept below the street lines above.

There are also city imposed constraints on surface excavation for the two centre stations, one in each contract which has led to some unusual "pipejack roof" construction.

"The area is part of the ancient settlement and has possible archaeological importance," says Schulz.

A ruling says that previously undisturbed ground, mostly under the street must be left intact for the top 5m and so contractors have had to find a way to support the top layer while excavating underneath.

Thailand's two largest contractors won the work, Itai Thai Development, ITD for the Hua Lamphong section and Ch Karnchang on the continuation underneath the Chao Phraya river. Both started in March 2011 and both have had some difficulties and hold-ups with the tunnel drives but both are currently in progress. Completion to a revised schedule is due in mid-2016.

Property acquisitions have held up some of the station work and recently an extension of time was granted for the contractor to allow for the difficulties.

### SCHEDULING

"Fortunately the completion of the drives is not on the critical path" says Schulz, "which is determined by the rolling stock and signalling works contract, a sixth contract which is just at the start of procurement."

For Itai Thai, one of the main difficulties has been simply fitting its works into the congested street junctions around the main station and coping with limited site space. It is launching its drives from the end part of a cut and cover construction needed to link the tunnels to the existing line terminus.

This requires work underneath one of Bangkok's busy roads which has required the contractor to split its worksite into three sections, one occupying the middle of a roundabout for the site depot, the next for TBM launch and spoil mucking from an access pit to one side, in front of the railway station, and a further site 200m away occupying a narrow strip in the main road, which serves as a segment store and materials depot. Engineers have to constantly cross the roads from one to the other, and ironically for once, the often slow pace of the traffic in Bangkok is a blessing.

But it makes work organisation difficult. "We have to use a just-in-time method to bring the segments from the storage area to the TBM access pit," explains Itai-Thai project manager at the main contract site Thavesak Rungpiriyadech.

Additionally he says, part of the work is being done underneath heavy road decking for the construction of the 170m long cut and cover box linking the old Blue Line to the new. An opening 18m by 18m at the far end of this is where the 15m deep tunnel access pit is located for the for the TBM work

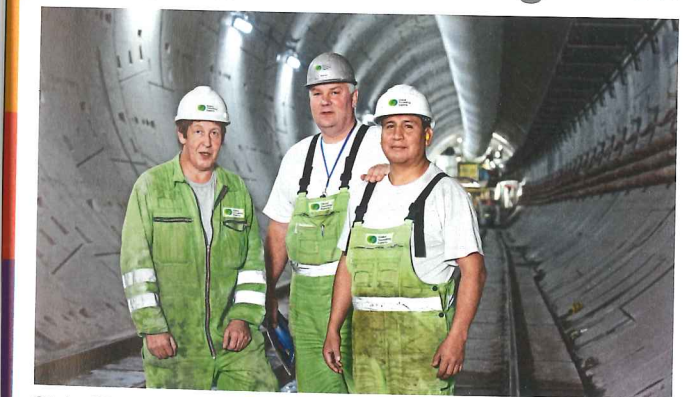
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## Contact us

Alex  
Conacher



**Editor**  
Alex Conacher  
Tel: +44 20 7406 6616  
aconacher@tunnelsonline.info

Nicole  
Robinson



**North America Editor**  
Nicole Robinson  
Tel: +1 612 940 2780  
nrobinson@tunnelsonline.info

Sally  
Spencer



**Contributing Editor**  
Sally Spencer  
sspencer@progressivemediagroup.com

**Contributing Editor**  
Keren Fallwell  
kfallwell@progressivemediagroup.com

**Regular Contributors**  
Adrian Greeman, Bernadette Ballantyne,  
Partick Reynolds, Rhian Owen,  
Roland Herr

**Associate Publisher**  
Jon Young  
Tel: +44 20 7406 6622  
jon.young@worldmarketintelligence.com

Keren  
Fallwell



**Sales Manager**  
Marcela Ahmeti  
Tel: +44 20 3096 2607  
marcela.ahmeti@tunnelsonline.info

Marcela  
Ahmeti



**Account Manager**  
Tom Willard  
Tel: +44 20 3096 2608  
twillard@tunnelsonline.info

**European Sales**  
Randolf Krings  
Tel: +49 611 5324 416  
Fax: +49 611 5324 519  
rkt@emcmedia.de

### Head Office

World Market Intelligence  
John Carpenter House  
7 Carmelite Street  
London EC4Y 0BS  
United Kingdom

Tel: +44 20 7406 6622  
Fax: +44 20 7936 6813

www.tunnelsonline.info  
editor@tunnelsonline.info

### Editorial

### Sales

### Production

**Production Controller**  
Loraine Lee  
Tel: +44 20 8269 7799  
Fax: +44 20 8269 7840  
llee@progressivemediagroup.com

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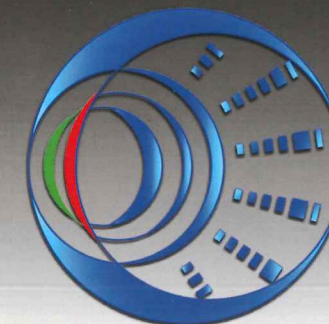
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