INTERNATIONAL EDITION
February 2016

# Tunnels AND TUNNELLING

+ India

Czech hand mining

Ground risk

# RESERVOIR SLOG

*Teams connect an abandoned reservoir to the Montreal water network despite challenging geology*

# ENTER THE NIMBY

A PUBLIC CONSULTATION has opened for a new road crossing of London's River Thames. The idea is for a new tunnel to the east of the city to relieve the enormous traffic strain on the existing Dartford Crossing.

For over 50 years, the Dartford Crossing has provided the only road crossing of the Thames east of London. This spectacular choke point, partly caused by tollbooths, consists of two bored tunnels and a bridge. Highways England claims 50 million crossings per year, of which 25 per cent are freight vehicles. The freight proportion is predicted to increase to 34 per cent by 2041.

Amazingly the crossing is closed (partially or fully) over 300 times per year due to 'incidents'. It can take three to five hours to blockages to clear to normal levels following a typical closure. Motorists have the option to cancel their journey, wait in traffic, travel to the Blackwall Tunnel (add 50km), or travel around the western side of London's ring road, the M25 (add 160km).

Another eastern road crossing of the river is really good news for motorists. And so a proposal for a new dual carriageway has been issued. Costs are not yet known, although GBP 3.4bn (USD 4.93bn) is mooted, and the government has invited public feedback on a few variations of the route.

Local residents are not happy. Local residents are not expected to be happy. Multiple petitions have been launched to stop the project. Their issues are mostly understandable. Some people could lose their homes, albeit with compensation. Others will complain about years of construction. Yet more will fear damage to the environment, or local communities.

But comments from a Not In My Back Yard (NIMBY) movement can be fascinating to read, despite their negativity. Any argument is seized upon. In the case of the Lower Thames Crossing, a popular opinion seems to be that investing in new infrastructure actually increases congestion.

Leaving aside that Transport for London would have been thrilled to learn that they could have relieved congestion on London's Central Line simply by cancelling the Crossrail project and running a reduced service on the Piccadilly Line, the notion that infrastructure investment causes congestion has been rubbished in a more serious fashion on several occasions.

For example, in 'Misconceptions and Exaggerations about Roads and Road Building in Great Britain' a 2008 paper by David Bayliss for the RAC Foundation (a UK transport policy and research organisation) Bayliss argues that although traffic indeed moves to the new infrastructure, congestion is in fact eased on existing and overtaxed routes. Or even in the worst case for congestion statistics, existing but as yet unrealised demand is met.

Then there is the fact that, in 2008, some 70% of journeys by distance took place on the road. Although as a society, green solutions and mass transit are desirable solutions to moving the population around, it is simply not always possible. So anything that makes these journeys more efficient is a green and sustainable result for society.

A vital project such as the crossing should not be at risk from the objections of a few NIMBYS, but fortunately these decisions are rarely theirs

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

*Alex Conacher*
*Editor*

*Cover*
The cover shows engineers celebrating breakthrough on the Rosemont Reservoir tunnel project


*Next issue*
In the next issue of Tunnels and Tunnelling, we cover projects from Peru, Mexico and Austria, as well as shaft and caisson work, improvements to the design life of screwbolts in use on London's Crossrail project, and a BTS report on the Canning Town project.

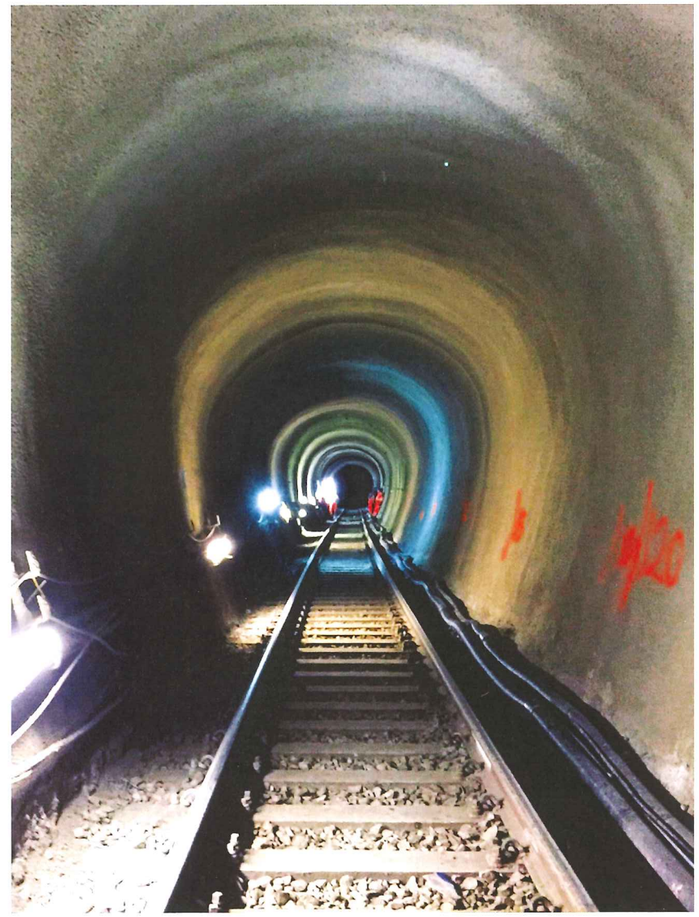
## *This month...*

### 10 YEARS AGO

Ghella Sogene CA broke through on Line Three of the Caracas Metro in Venezuela. The 5.8m-diameter Lovat EPBM was launched at the beginning of March 2005 since which time it has bored 2,300m. The ground was described as schists, sand and clay with water pressures of 1 bar. The TBM will now be used for a second parallel drive. Additionally, Odebrecht announced it had launched its TBM on the left tunnel of the La Rinconada to Coche stations stretch of Line Three. The 2,380m-long tunnel will pass through rock formations to La Rinconada and sandy surfaces carrying a high water flow at Coche. Excavation should be complete by September of this year.
*Tunnels and Tunnelling, February 2006, p.6*

### 40 YEARS AGO

Breakthrough is imminent at St Gotthard. The 16km-long St Gotthard road tunnel, when completed in 1980, will be the longest road tunnel in the world and will provide a year-round route for traffic travelling between Switzerland and Italy. The twin tunnels, and smaller safety tunnel, have been divided into two sections for construction purposes: a northern 6.8km section and a southern 9.5km section. The northern section is now fully excavated but the southern section has been delayed by a zone of very poor rock. Breakthrough on the south is expected in March. In contrast with the existing railway, the road tunnel will follow the valley to avoid deep alluvial fill.
*Tunnels and Tunnelling, February 1976, p.14*



*Above: The Farnworth Tunnel upgrade project, see page 32*

## Key people in this issue

**TOMAS ZITKO**
Tomas is a project manager at Sudop Praha, a design, consulting and engineering company based in the Czech Republic. In this issue of Tunnels and Tunnelling he writes about some of the hand mining techniques that are common in the country. At the time of writing he was with Czech engineering company Pohl where he worked on interceptor sewers for Prague and Pilsen, as well as the upgrade of Benesov's water system. Prior to that he worked at Gall Zeidler Consultants, ILF Consulting Engineers, Mott MacDonald and Subterra. His paper can be found on page 44.

**STEVE HUNT**
Steve is a senior tunnelling technologist at CH2M. He has more than 38 years of experience with tunnelling and underground construction, primarily for water and wastewater projects. He is a professional engineer with BS and MS degrees in civil and geotechnical engineering from the University of Illinois, and has authored or co-authored more than 30 papers on design and construction of shafts and tunnels including at least 15 related to tunnelling in cobbles and boulders. In this issue he writes about risk related to tunnelling through cobbly, bouldery group. His paper can be found on page 37.

# ARUP-ATKINS WIN THAMES TIDEWAY WEST DESIGN AND ENGINEERING WORK...

GREAT BRITAIN — Atkins and Arup will provide design and engineering services on the west section of the Thames Tideway project. The contractors for this section, Bam Nuttall, Morgan Sindall and Balfour Beatty, will tunnel 6km of 7.2m-diameter tunnel from the Acton Storm Tanks at the extreme west of the scheme, to the start of the central section at Carnwath Road.

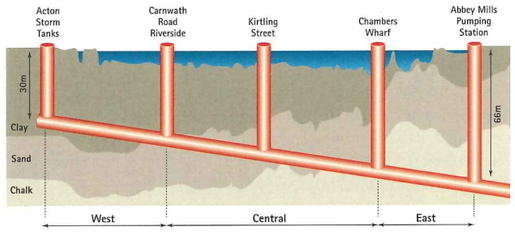
The west section is largely through clay, entering a section of sand at its eastern end. Valued at GBP 416M (USD 602M), it incorporates seven separate work sites along the route.

Mobilisation work for the western section begun in September last year with completion scheduled for 2022.

Upon completion, the Thames Tideway Tunnel will ensure the capital's sewer system is fit to support its projected population for at least the next 100 years, and will tackle the issue of discharges of untreated sewage that currently enter the River Thames on a regular basis.

The new 25km tunnel will be the largest infrastructure project ever undertaken by the UK water industry.

Nick Roberts, UK CEO at Atkins, said: "A healthy River Thames plays an essential role in the wellbeing and prosperity of the City of London and its people. The Thames Tideway Tunnel will help transform the river and we are very pleased that JV chose the valuable experience, expertise and approach we've developed with Arup from projects such as Crossrail. We look forward to playing our part in promoting a positive change in the relationship that Londoners and visitors have with the Thames."




*Thames Tideway project scope showing geological and sectional divisions*

Alan Belfield, UKMEA chairman for Arup said: "The Thames Tideway Tunnel is one of the UK's most challenging, yet important, infrastructure projects. We have already made great strides in creating a cleaner and safer River Thames but there is a clear need to modernise our essential infrastructure. Partnerships such as ours with Atkins will play a pivotal role in driving forward these major feats of engineering and we look forward to working together on this unique project to see the benefits it will provide to the city."

## ... and Mott MacDonald design Tideway East

GREAT BRITAIN — Mott MacDonald will design the eastern section of the Thames Tideway sewer tunnel in London. The section will be constructed by a joint venture of Costain, Vinci Construction Grands Projets and Bachy Soletanche.

The east section package includes the construction of two TBM-driven tunnels – a 5.5km section of the main 25km tunnel and a 4.6km connecting tunnel for combined rainwater and wastewater. The main tunnel will have an internal diameter of 7.2m, while the connecting tunnel will be 5m. The project will be 45 to 65m below ground. The east section also requires five shafts from 17 to 25m in diameter sunk to 72m using diaphragm walls.

According to a spokesman, an optimisation phase, which includes design and methods, is almost completed and the design team are delivering the first conceptual designs using state-of-the-art building information modelling models and processes. The works are scheduled for delivery in 2023.

Michael Francis, Mott MacDonald's project director, said: "It is fantastic to be involved in the creation of one of London's most significant infrastructure projects. The East works package is the deepest section of the project, with tunnels driven by slurry TBMs deep in the chalk up to 70m below the water table. The deep shafts will be constructed using diaphragm walls and the complex hydraulic structures to divert flows require soil mixing ground treatment, secant piles and high-quality concrete meeting the 120 year design life."

## Normet to acquire Meyco dry spraying

GLOBAL — Normet announced on 19 January it has agreed to acquire from Atlas Copco the assets of the Meyco dry spraying business consisting of the models Piccola and GM. The parties have agreed not to disclose the purchase price.

"This acquisition is a good strategic fit for Normet as it broadens the offering for our existing customers in mining and tunnelling," said Tom Melbye President of Normet Group and Managing Director of Normet International. "It also complements our offering of new technologies in Construction Chemicals, especially with respect to the application of the Tamseal 800 waterproofing sprayable membrane."

The acquired business will form Normet's Meyco Dry Spraying product line, which will be headed by Tom Kurth, former managing director of Meyco Equipment and business development manager in Atlas Copco Meyco.

The manufacturing of the dry spraying products will continue in Switzerland. Sales and service of Meyco dry spraying products will be handled through established distributors as well as Normet's own network. The distribution of spare parts will be managed through Normet's Global Logistics Centre in The Netherlands.

## El Teniente to expand

CHILE — Züblin has been awarded an EUR 100M (USD 109M) contract to expand the El Teniente copper mine. The German construction company has been carrying out tunnelling work at the mine since March 2014. The 10.7km expansion will be carried out by drill and blast with a cross sectional area ranging between 2.7 x 2.6m and 9.7 x 8.6m. Grouted bolts (7 to 24 bolts of 2-4m in length per metre), mesh and sprayed concrete (70 to 100mm thick) will support the ground.

"The main challenge in this copper mine, the largest in the world, are the seismic conditions and geologic forces", says Thomas Birtel, CEO of Strabag, which owns Züblin. The work will increase the life of the mine by 50 years and is being undertaken some 80km south of Santiago for Codelco, the world's largest copper producer. The mine first opened in 1904 and produces more than 400,000m³ of copper every year. Work is scheduled to complete by the end of 2016.

# GOVERNOR HALTS TUNNELLING ON RECENTLY RESUMED SEATTLE TUNNEL

USA — Washington governor Jay Inslee suspended tunnelling on the SR99 tunnel project 14 January, pending the investigation of a sinkhole.

The Washington State Department of Transportation (WSDOT) said a sinkhole developed within contractor Seattle Tunnel Partners' work zone near South Main Street, about 35ft (10.7m) north of the access pit, at approximately 9pm Tuesday night. It is located more than 100ft (30.5m) south of the cutterhead's current location, in ground that crews mined through last week. STP filled the sinkhole overnight with 250cu.yd. (191cu.m) of concrete.

"This section of the tunnel drive is protected by an underground wall built by STP before tunnelling." WSDOT said. "The wall was designed to isolate ground movement and protect the nearby Alaskan Way Viaduct. A manual survey of the viaduct conducted after the sinkhole developed found no movement."

WSDOT and STP will continue surveying and monitoring the ground, viaduct, utilities and other structures. The cause of the sinkhole is still under investigation. STP is analysing the portion of the tunnel that crews have excavated since mining resumed. There is no indication that any other locations have experienced ground loss.

The protocols STP outlined to enhance monitoring were used in the first 1,000ft (305m) of tunnelling and WSDOT said it is "disappointed they were not used when STP restarted tunnelling in December 2015." STP has several hundred feet of mining before they reach the next planned maintenance stop. Before leaving the maintenance stop, STP's operational protocols will undergo an additional review by an expert to assure public safety.

In a separate incident on 12 January, STP's barge filling operation resulted in a barge listing beyond STP's control. As a result the barge was either let go or broke free from the pier, spilling tunnel spoils into Elliott Bay, and drifted out of control damaging both Terminal 46 and Pier 48.

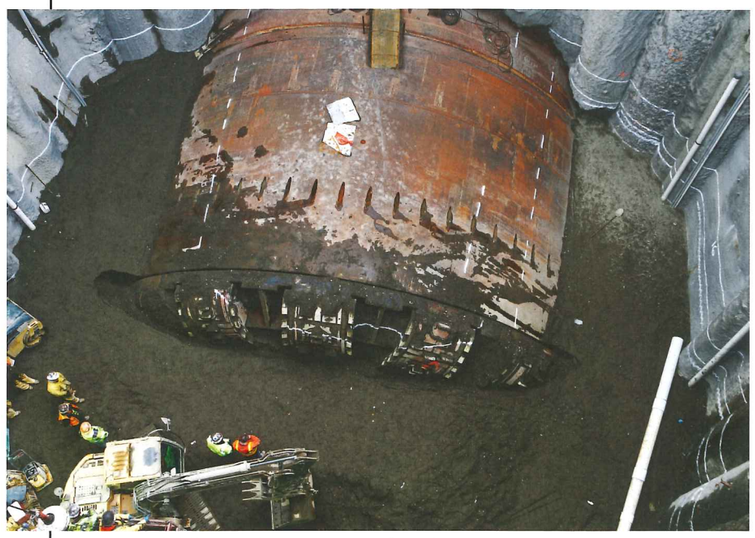
STP resumed tunnelling that same evening, using trucks to remove excavated material while they continued working to resolve the barge issues. The contractor's inspection of pilings at Terminal 46 is ongoing. The terminal is structurally sound, but crews noted some damage to pilings. STP is preparing to install fenders along the pier that will allow them to continue safely barging from this location.

Work to move material from the damaged barge to a second barge is expected to be completed this week. Once complete, STP will be able to determine the amount of clean material that spilled into Elliott Bay. Repairs will be needed before the damaged barge can be used again in the tunnelling operation.

In light of both incidents this week, WSDOT issued a letter to the contractor on Thursday stating the suspension and requiring the contractor complete a detailed analysis and modify tunnelling operations to ensure appropriate ground control. "STP will not be allowed to resume tunnelling until their analysis and work plans meet the satisfaction of the design-build contract and WSDOT's experts."

The tunnel contract contains a few different mechanisms for stopping work. In this case, WSDOT suspended work "for cause" per section 14.2 of the contract, which says the state can suspend work without liability to WSDOT under a number of conditions, including the contractor's failure to "correct conditions unsafe for the project personnel or general public."

This suspension for cause only addresses tunnelling operations involving the TBM, including loading of barges at the site. It does not affect any of the other work under the design-build contract with STP or in any other contracts being managed by the viaduct programme.



*Recent work filling in the repair pit in Seattle, prior to excavation restart*

## *LTA awards TEL contracts*

SINGAPORE — The Land Transport Authority (LTA) has awarded three station contracts for the Thomson-East Coast Line (TEL). The contracts, worth a total of about USD 663.5M cover works for the Tanjong Rhu, Katong Park and Marine Terrace stations.

Tanjong Rhu Station and its associated tunnels was awarded to a Bachy Soletanche Singapore - Wai Fong Construction JV. Katong Park station and its associated tunnels has been awarded to Shanghai Tunnel Engineering Co. (Singapore). Marine Terrace station and its associated tunnels has been awarded to a Ssangyong Engineering & Construction Co. - Hyundai Engineering & Construction Co. JV.

Construction should begin in Q1 2016 and complete in 2023. A spokesman added, "The 13km East Coast stretch of the TEL will connect commuters living in the eastern parts of Singapore and who are not directly served by the rail network currently, such as those in Tanjong Rhu, Siglap, Marine Parade, Upper East Coast and Bedok South, to the heart of the city.

"As part of the 43km-long TEL, the East Coast stretch will also connect commuters to the Thomson stretch of the TEL, which serves the north-south corridor. The East Coast stretch will have nine stations, including an interchange with the DTL."

### *First Street Tunnel TBM finishes bore*

USA — The Skanska/Jay Dee joint venture completed the 2,700ft (822.96m) TBM drive for the First Street Tunnel on 22 December, DC Water announced.

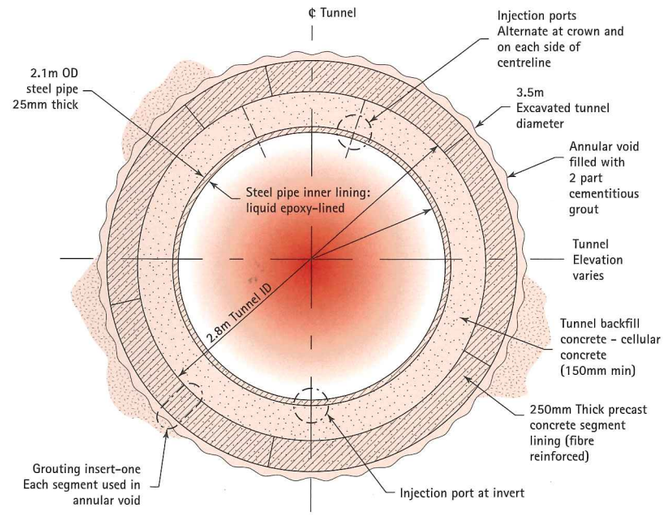
The alignment is 100ft (35m) underground under First Street NW in Washington, D.C. This tunnel segment will ultimately connect to the 5-mile- (8km-) long Northeast Boundary Tunnel in 2022. From 2016 to 2022 the First Street Tunnel will store and then pump combined sewage up into the existing sewer system during and after rainstorms. The First Street Tunnel is designed to mitigate flooding from undersized sewers in the Bloomingdale and LeDroit Park neighbourhoods.

DC Water selected Skanska/Jay Dee Joint Venture for the project in 2013 and the TBM launched this summer. Scott Hoffman, Skanska/Jay Dee project manager for the First Street Tunnel said the joint venture team was committed to this project and the challenge of conducting heavy civil work in a densely populated urban area. Hoffman said: "It's a great accomplishment to have Lucy finish the tunnelling portion of the work just in time for her to go home for the holidays."

This was the second DC Water TBM to complete a

## *BTS calls for presentations*

The BTS Conference 2016 will take place on 11 and 12 October 2016 at the Queen Elizabeth II Conference Centre, Broad Sanctuary, Westminster, SW1P 3EE. Engineers wishing to give a presentation should submit a short 250 word synopsis with a drawing or figure and a speaker biography to the BTS (paulperry@ch2m.com) for consideration by 26 February 2016.




*Budding speakers should submit a synopsis, figure and biography by 26 February*

### *Boris Johnson opens Lee Tunnel*

GREAT BRITAIN — The Mayor of London, Boris Johnson, officially opened the Lee Tunnel sewer project in January. The tunnel, the first of two new high-capacity sewers in to serve Britain's capital is the largest project in the history of Britain's privatised water industry.

The GBP 678M (USD 971M), 7m-diameter Lee Tunnel runs 6.9km from Thames Water's Abbey Mills pumping station and will act as a collection and storage tank before transferring the flows to Beckton sewage works, which Thames Water has expanded by a further 60 per cent to manage the increased volumes.

The tunnel was dug through chalk at high water pressures and lined with steel fibre reinforced concrete.

The team used two 30.6m long shutters to cast a 300mm thick, steel-fibre reinforced secondary lining, reducing the previously bored 7.8m internal diameter to 7.2m.

## STONEHENGE DESIGN CONSULTANCY AWARDED

GREAT BRITAIN — An Arup Atkins JV has been appointed as the design consultant for the Stonehenge Tunnel project. The project is part of the A303 Amesbury to Berwick Down Improvement Scheme, which also includes a bypass of nearby village Winterbourne Stoke.

The team will develop options to take through public consultation and up to a preferred alignment announcement. The package of works is worth an expected GBP 17.5M (USD 25.31M).

The A303 trunk road links London with the South West and is a key route for long distance commercial and holiday traffic. The scheme will unlock a pinch-point that has restricted the economy of the South West while enhancing the world heritage site at Stonehenge. This scheme is an integral part for creating a A303 'expressway' to the South West region.

Subject to statutory procedures, the proposed scheme is on target for construction work to start by April 2020.

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

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

# HELSINKI-TALLINN TUNNEL MOA

FINLAND/ESTONIA — Political leaders have signed a memorandum of understanding stating the intention to improve connections between the two countries. Notably this includes a long-mooted tunnel between the cities of Helsinki and Tallinn.

The geography means that a land route between the two cities is prohibitive, and a two-hour ferry trip is just about the only option. A subsea tunnel would reduce journey time to 30 minutes. Additionally, plans to link Tallinn to the European high-speed rail networks could be extended to Helsinki.

A recent pre-feasibility study suggested that the tunnel could be constructed for less than USD 14bn. EU money is required for further studies.

Geological investigations will be needed for the subsea section of the alignment, but it is already known that the main problems are connected with geology at the possible portal locations on the Estonian side. The problems are mainly associated with weakly consolidated and water saturated Ediacara - Lower Cambrian layers. A 75 to 80m thick complex of weakly lithified and water-saturated silt and sandstones of the Kroodi Formation (Ediacaran around 55m thick) and Sämi Member (Lower Cambrian around 25m thick) covers the crystalline basement in the optional tunnel entrance area in Viimsi. This complex is also an important source of water supply for the Tallinn city area.

*Icebreaker ferries serve the region in the winter months*

## MARTA to upgrade tunnel ventilation system

USA — The Metropolitan Atlanta Rapid Transit Authority (MARTA) has inked a contract worth USD 198.5M to revamp and enhance its tunnel ventilation system (TVS).

Archer Western Construction will act as the primary contractor, while Cleveland Electric, R. F. Knox, WSP Parsons Brinckerhoff and up to eight Disadvantaged Business Enterprises will participate as subcontractors.

The six-year base contract totals USD 165m with an additional USD 33.5M in contract options that include an extended warranty, hardware refresh, and provisions for long-term system operations and maintenance.

The tunnel ventilation system covers about nine miles of subway tunnel and underground rail stations, about one-fifth of the rail system's total footprint.

MARTA's TVS includes a network of fans and dampers that effectively control and direct air flow during normal rail operations and in emergency situations.

MARTA interim assistant general manager of capital programs and development David Springstead said: "MARTA is ahead of the curve for dedicating a significant portion of its capital improvement budget to upgrading our tunnel ventilation system.

"In the transit industry, this is the largest single contract focused on this type of enhancement."

The improvement project is set to commence in early 2016.

## Rogue state constructs nuclear test tunnel

NORTH KOREA — Satellite imagery from late 2015 indicated North Korea was excavating a new tunnel for nuclear testing at its Punggye-ri nuclear test site. It was thought to be the fourth tunnel to be constructed at the site. At the time, the secretive dictatorship had conducted only three nuclear tests. In January 2016 however, Pyongyang claimed it had detonated its first hydrogen bomb.

Analysis of the satellite imagery has been conducted by Yonhap, a large South Korean news agency, and 38north, a website devoted to the study of North Korea.

New site structures were apparently visible at the worksites on Mount Musan, which houses the facility. Compared with earlier photographs, significant spoil dumps had become apparent. Earlier stacks of logs were no longer visible; it is thought that wooden supports might be used during excavation.

The tunnels are arranged around a central support facility. Analysis of site activity suggests the earliest test tunnel has been left without significant maintenance work, but later tunnels show continued activity.

Of particular interest to future projects at the site, US engineers have previously hypothesised (and debated some evidence) that repeated nuclear tests inside mountains can cause 'tired mountain syndrome' where the rock becomes weakened by repeated nuclear detonations, supposedly causing cracking and a diminished ability to contain subsequent nuclear blasts.

## ITACOSUF calls for safety officers

EUROPE — The Fourth European Forum of Road Tunnel Safety Officers has been set for 9 to 10 of March 2016 in Rotterdam, the Netherlands. The ITA Committee on Operational Safety of Underground Facilities (ITACOSUF), a co-organiser with the World Road Association (PIARC) and the European Commission has issued a call for attendees.

The Forum is open for Safety Officers from all over Europe and those which are appointed according to Directive 2004/54/EC have the chance to join the Forum free of charge.

The conference will be held in English.

Prior registration is compulsory and must indicate name, company, email address and concerned tunnel(s). Registration should be made as soon as possible by sending the asked details not later than 23rd February 2016 to secretariat@ita- aites.org

Every session with various presenters will be introduced by a keynote speaker and time for discussion with exchange of experiences is planned.

# TBM BREAKTHROUGH ON ROSEMONT TUNNEL

CANADA — Tunnelling for the Rosemont Reservoir, a project more than 38 years in the making, reached completion in November 2015, announced Robbins, manufacturer of the project's 3m diameter TBM.

Local contractor Foraction headed the excavation of the 4km-long tunnel with a TBM launch in December 2014. Roger Lepinay, Equipment Manager for Foraction, said the ground was "almost ideal", with a few difficult sections.

"Below Montreal there is mostly thinly bedded limestone, with some shale and intrusive igneous dykes," said project geologist Brigitte Gagné for company Exp Service. While the limestone averaged 100-150 MPa UCS, rock in the intrusives ranged from 100-300 MPa. The dykes were as small as 1m wide and as large as 100m. The contractor was able to successfully navigate these sections despite the varying rock strengths.

Even with geological challenges including some water inflows and over-break in small sections, the contractor was able to achieve advance rates of up to 38m per day in two shifts of 9.5 hours each, according to Robbins. Much of the ground was self-supporting, though the contractor installed rock bolts every 2.5m into portions of the tunnel crown, while mesh, rock bolts, and steel sheets were used in the sections of unstable rock.

The Rosemont reservoir was built in 1960 to increase water supply to the city and a geotechnical study for the tunnel was carried out in 1977. However, other major infrastructure projects soon took priority and the project was placed on hold. By 2010, the population of the city had increased dramatically and problems with the existing reservoirs put the project back on the fast track. The large reservoir that sat idle for decades will now be used to improve much of the city's water supply.

As of mid-January the contractor is working to ready the tunnel for installation of the carrier pipe, consisting of 2.13m I.D. pre-stressed concrete cylinder pipe (PCCP). Crews will then grout the pipe in place in preparation for the Rosemont Reservoir to come online.

*Rock in the intrusives reached up to 300MPa, but averaged 100-150MPa*

## *Hochtief to Build A7 Tunnel in Hamburg-Stellingen*

CANADA — Hochtief announced on 19 January it has been awarded an approximately EUR 154M (USD 166.77M) contract to construct Tunnel Stellingen in Hamburg with Franki Grundbau.

The future noise protection structure is part of the extension of the A7 highway in Hamburg and Schleswig-Holstein. Tunnel Stellingen is roughly 1km long. With Hochtief as technical leader, the joint venture will construct two cut-and-cover tunnel tubes with five lanes each and one emergency lane. The tunnel is one of three noise protection tunnels, the "Hamburger Deckel", which will be built within the framework of the expansion project.

"We are delighted to be able to bring in our execution competence into a further section of the A7. With this noise protection program, we offer the citizens of Hamburg better quality of life in the future", said Nikolaus Graf von Matuschka, CEO of Hochtief Solutions.

## *Jacobs becomes BASF's global engineering partner*

GLOBAL — Jacobs will provide engineering, procurement and construction management and integrated project management services to BASF. The contract will last three years.

Jacobs president for petroleum and chemicals, Gary Mandel said, "Our relationship with BASF spans many years, and we are delighted to further strengthen our relationship across the globe. This selection represents a strong endorsement of our international reach and EPCM capabilities, and we look forward to working alongside BASF to support its continued growth and success."

## *Strata chooses DSI as North American distributor*

NORTH AMERICA — Strata Worldwide has signed a deal with DSI to give the latter exclusive distribution rights to Strata products in North America. Strata produces mine safety technologies, communication solutions and emergency refuges as well as tracking and atmospheric monitoring systems. Strata's global commercial manager Ryan Fielden said: "We are thrilled to be teaming with DSI, a strong partner with a great reputation and longtime presence in the tunnelling industry."

## *Istanbul Metro breakthrough*

TURKEY — The TBM mining the 2,900m Yenimahalle to Veysel Karani section of the Istanbul Metro broke through in December. The drive took seven months.

The contractor, a joint venture of Gulermak, Kolin and Kalyon then began the process of dragging the machine through 200m of station to a 60m-deep access shaft to remove the 6.56m-diameter TBM. It will then be returned to Yenimahalle to drive the second tube.

The ground has varied from true mixed ground to soft ground with up to 4 bar face pressure applied. The tunnel is lined with universal reinforced concrete segments with an outer diameter of 6,300mm, inner diameter of 5,700mm and width of 1,400mm.

## Obituary

### BRADFORD FIELD TOWNSEND
***22 June 1955 - 24 Dec 2015***

Bradford Field Townsend, 60, of Bridgewater NH passed away unexpectedly at home Christmas Eve 2015. He was with his beloved wife and mother at the time of his death.

Brad was born in Beverly, MA on 22 June 1955. He went to Burr & Burton high school in Manchester, VT. He obtained a B.S. in Natural/Environmental Science at Johnson State College in Johnson VT in 1979 and a MS in Civil Engineering at the University of New Hampshire, Durham NH in 1985.

Bradford's work as a civil engineer both in the United States and internationally encompassed the design and construction of tunnels, mines, bridges, and highway and rail transportation systems.

His engineering career began at Haley and Aldrich in 1986 where he worked on projects in the New England area that included foundations for buildings and bridges, soil and rock excavation, and water, pedestrian, subway, and highway tunnels.

He later worked on projects in Cairo and Bangkok.

In 1994, he joined Louis Berger International and continued to work in Asia on the BTSC Mass Transportation project in Bangkok involving the design of 25km of elevated heavy rail mass transport and 25 stations, and the Hai Van Pass Tunnel Project in Vietnam which included the design of 6km of tunnel and 2 km of bridge work. From 2000 to 2005, he was the Deputy Chief Director of Engineering for the Taiwan High Speed Rail project

*Bradford Field Townsend*

working for Parsons Brinckerhoff International. The high-speed rail project required the design and construction of 47km of mined and cut and cover tunnels, 250km of viaduct structures, and 32 km of cut and fill embankment.

Upon returning to the United States, Bradford joined Hatch Mott MacDonald working on the San Francisco Downtown Rail Extension; a multi-modal transportation facility accommodating buses, commuter rail, and future high speed rail operations. To care for his parents, he moved back to New Hampshire in 2012, and joined Parsons Transportation in a vice president role overseeing large transportation bridge and tunnel projects. He later joined Dr. Sauer and Partners in early 2015.

Throughout his career, Bradford assumed a prominent and noted role in the civil engineering and tunnelling community. He published several articles in the North American Tunnelling and ASCE Journals, and for over twenty years presented at a variety of global engineering conferences.

His projects have won the ACEC Engineering Excellence Award, and ASCE National and Regional Excellence Awards.

Although highly accomplished as a civil engineer, Bradford considered his own construction company his pride and joy. In 1979, after graduating from Johnson State College, Bradford be- came the owner and manager of Lone Pine Construction, concentrating on residential and light commercial projects, general site civil development, and water front work.

After becoming an engineer, Bradford continued to operate Lone Pine as a construction and engineering company until his passing.

Brad is survived by his wife Sandie Kuo Townsend, his mother Helyn Acosta Townsend, his sister Lisabeth Carol Townsend, two aunts and many cousins. Brad is predeceased by his father John Burnett Townsend.

Brad cherished his time at home on Bridgewater Hill with his love for the land and the close knit community. He enjoyed motor biking, skiing and the true spirit of the holidays. Friends around the world will always remember his vibrant smile and a loud "URRR" signifying a bond of friendship.

The family invites donations in Brad's honour to the St. Jude Children's Research Hospital (www.stjude.org).

**Larry Johnson, Parsons Corporation**

## *Follo Line contract awarded to Pöyry*

NORWAY — Norway Societá Italiana per Condotte D'Acqua S.p.A. has chosen Pöyry to carry out rock and tunnel engineering for the Follo Line in Oslo, Norway, the consulting and engineering firm announced on 25 January.

The Follo Line connects Oslo with the city of Ski in the east-bound Follo district. Pöyry's assignment includes most of the design needed for 5.5km of tunnels close to the city centre of Oslo, 4km of which is for high-speed train traffic.

Condotte is the EPC contractor for which Pöyry is engineering, and the end client is the Norwegian National Rail Administration. The tunnel will be excavated using drill and blast and drill and split methods. All engineering will be carried out as Building Information Modelling (BIM).

According to Pöyry, the project includes some unique challenges, such as the existing underground facilities and the relocation of the underground River Alna. "This is the first large transportation engineering assignment we have won in Norway. Our experts in Norway and Finland are working jointly to tackle the challenges of the assignment in an innovative and reliable way that is characteristic to our work," said Mikko Inkala, president of infrastructure design at Pöyry.

The value of the order is not disclosed. The order has been recognised within the Regional Operations order stock in Q1 2016.

The Follo Line tunnel system will be the longest in Norway with a total length of 20km and a maximum train speed of 250km/h. It will meet the increased demand for rail traffic capacity in the greater Oslo area, and the project should complete by the end of 2021.

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

editor@tunnelsonline.info


*Left: The Los Angeles County Metropolitan Transportation Authority (Metro) held a TBM lowering ceremony on February 1 for the Crenshaw/LAX Line. The TBM, a 6.5m-diameter Herrenknecht machine, will excavate twin 1.6km tunnels at the northern end of the new rail line. The 13.7km Crenshaw/LAX Line is a USD 2.058bn light rail line that is being built by Walsh-Shea Corridor Constructors, comprised of Walsh, Shea, HNTB, Comstock and Arup. It is expected to open in 2019*

# INDIA'S GROWING PAINS

Metro projects and hydropower schemes continue to drive India's tunnelling market, and more opportunities are yet to come but challenges remain in the competitive market, **Bernadette Ballantyne** reports

UNTIL THE turn of the new millennium India's tunnelling market was dominated by hydropower and irrigation tunnels, many of which meant drilling into the challenging geology of the Himalayas. "These are the toughest ground conditions in the world, closely followed by the Andes and then the Alps," says Manoj Verman, president of the Indian National Group of the International Society for Rock Mechanics and an independent consultant on tunnelling and rock mechanics. "The geology is very varied. It is not uncommon to encounter weak zones, shear zones, fault zones and water in the same path," he says noting that the high overburden stresses from the mountain can also cause problems. Combined with the inaccessible nature of some of the locations and the climatic extremes that include snow and flash flooding, working conditions are inhospitable at best and impossible at worst. It is clear to see why projects here are so challenging.

## EARLY TBM HURDLES

Dealing with the hard and changeable Himalayan rock has traditionally been a drill and blast affair, but the use of TBM appears to be gaining momentum despite an inauspicious start. "In mountainous regions TBMs have been used and the first three projects were a disaster," says Verman. "There is frequently changing geology and if a TBM goes fast it can get stuck and that is a nightmare. If the height of the mountain is very high it stresses too much and if the rock is soft then it squeezes, under the same height of overburden if the rock is strong then it will burst so these two are extreme cases and they both happen under high stress."

An early example of a stranded TBM was on the Dul Hasti hydropower project in the Kishtwar district of Jammu and Kashmir, which began preliminary construction in 1985 and became operational in 2007. Shear zones regularly crossed the 9.64km head race tunnel alignment and water seepage was high leading to tunnel roof collapses that eventually buried the TBM, leaving it beyond salvation. In Himachal Pradesh on the Parbati 2 hydropower project another machine became stuck after large inflows of water gushed into the tunnel. "On the Parbati project it was stuck for three and a half years because of bureaucratic delays," says Verman remarking that technical issues are not the only problem that tunnelling schemes in the Himalayas have had to face.

On a third scheme, the 12.1km headrace tunnel for the Vishnugad - Tapovan hydropower project the double shield TBM started off very well but was trapped three times, most notably on Christmas Eve in December 2009.

## BETTER PROGRESS

However there have been some more positive breakthroughs. In June 2014 contractor and TBM manufacturer Seli announced that it had completed 14.7km of tunnelling on the Kishanganga hydropower project in Kashmir, mainly for construction of the 12km headrace tunnel. Revealing average rates of over 400m per month and a maximum of 816m in a single month, the scheme has been widely recognised as a huge breakthrough for mechanised tunnelling in the Himalayas. "This tunnel was a tremendous success," says Verman pointing to other forthcoming schemes that are planning to use TBMs. Client THDC India has appointed Hindustan Construction Company (HCC) to use a TBM for delivery of a 10m diameter, 12km long head race tunnel for the 444MW Vishnugad-Pilpakoti hydropower scheme in Chamoli in the state of Uttarakhand. The TBM is scheduled for delivery and assembly on site in February 2016.

Long awaited success in the mountains combined with a huge demand for TBMs to build a growing number of city wide metro schemes,

*Below: Chennai Metro worksite; view from a crane*

***Bernadette Ballantyne***
Bernadette is a regular contributer to *Tunnels and Tunnelling*

means that TBM manufacturers are upbeat about the prospects. TBM manufacturer Robbins established its Indian subsidiary in New Delhi in 2005.

"We started by supplying 10m double shield TBMs to contractors for an irrigation water supply tunnel which is 43km long. It would be the world's longest tunnel without intermediate access once completed," says Kapil Bhati, general manager for Robbins India, noting that the company's 10m diameter machines are the largest in operation in India today. "The tunnel will take the water from a river and then over to a drought affected areas irrigating 500,000 hectares of land and further providing drinking water. We have completed around 25km as of now with two TBMs. We are still continuing and expected to complete 2.5 years from now," he says.

Of course such a huge job has not been without its challenges and although boring of the outlet began in 2007 access to the inlet end was not available until 2011 due to land acquisition issues.

"After that advancements were pretty good even with geology being more difficult than anticipated. We are still doing around 300m/month average on each side of the tunnel so the production average is good in spite of the hard rock and tough geology," says Bhati.

Another water tunnel transferring flows from the same river, is also underway using a third Robbins 10m diameter machine. The tunnel is half way through with three years to go, says Bhati. A fourth 10m diameter machine is also building a 12km water transfer tunnel.

## METRO GROWTH

As these schemes roll on Robbins has also been busy supplying and supporting machines for metros in India's bustling cities. "Soon after the irrigation tunnels the metro projects started," says Bhati and the company began by supplying machines to Delhi and then Chennai. "Delhi Metro was totally soft ground so we supplied a spoke type EPB machine. Those machines performed very well and had very good advance rates.

"The geology of Chennai is mainly soft but there are a couple of areas where there is rock or mixed ground and then we have supplied a mixed face EPB machine for that geology," he says.

"The result has been a more challenging bore in Chennai with rock at the bottom and soft ground at the top combined with ingress of water. "Cutter changes and interventions were challenging but we have still been successful. There are around 200m left to bore."

In Jaipur which is currently building the first phase of its metro starting with a 12km east–west connection, 2.8km of which are underground, the company met with soft ground. "The contractor had two old Robbins machines in stock so we refurbished those machines for the contractor and those are being used. The main challenge her is the heritage structures over the top. It is an old city," he says noting that in the areas


*Below: Break through on a Mumbai water tunnel project*







where the metro transitions from elevated to underground there is just 5m of cover and yet the marginal tolerance is just 1mm.

## TIP OF THE ICEBERG

These are just the tip of the metro iceberg. "Right now there are metros being built in New Delhi, Chennai, Calcutta and Bangalore. Elevated and underground both," says Sanjib Bhattacharya, chief of TBM tunnelling at ITD Cementation India, which is comprised of Italian Thai Development Public Company Limited with the Indian branch of the UK's Cementation. In his 22 years with the company Bhattacharya has delivered 50km of traditional tunnelling with NATM and 21km of TBM routes. "We just completed 7km of TBM tunnelling in Delhi. I was the project manager and out of 7km there were four EPB TBMs, two mixed shield and two soil all from Herrenknecht. In Delhi out of 36 machines, some 19 were Herrenknecht," he says.

The Delhi metro is now undertaking its third phase of construction (see feature, page 27) which will result in a further 160km of new lines 54km of which are underground. At its peak in mid 2014 there were 26 TBMs working simultaneously. The tunnelling is over 80 per cent complete as Tunnels and Tunnelling goes to press and has not been without its challenges. Bhattacharya says that one particularly tough section was a 1.25km drive that ran beneath Delhi airport's runway for a distance of 400m meaning that the contractor was not able to carry out geotechnical investigations.

"This was very unpredictable because the geological data was not there. We designed our machine cutterheads and cutting tools on the basis of available geological parameters. It was around rock, we encountered quartzitic rock of around 200-210Mpa. Very, very hard. So in accordance with that we designed our machine to 250MPa. But unfortunately when we entered the airport area where the survey was not possible we encountered 350MPA," says Bhattacharya. As a result the construction costs ballooned from USD 14 to USD 15 per metre to around USD 35 as the hard rock quickly ate up the cutters. "It was a huge cost and meant that we were only getting four or five metres per day."

As a result progress on this section was two to three months behind schedule, says Bhattacharya, however he points out that better progress on another drive where they avoided the rock and used the soil EPB machine made back the time.

Despite having taken cores every 50m the nature of the airport site prevented investigation in this area and Bhattacharya says that the client accepted this when the contractor made a claim for the additional costs.

"In India contracts are very rigid. 400m survey was not possible so we put a claim in and this was (logically) accepted by DMRC as the data couldn't be got in advance."

## CRITICAL GEOLOGICAL DATA

As this experience shows, obtaining geological data is critical for any tunnelling project and is an area where Verman says that clients themselves need to put in more effort in the planning stages if they want to see their projects succeed. "The biggest lesson I would offer clients is 'please investigate more'. What is absolutely lacking in the country is proper site investigation or geotechncial investigation before the project," he says pointing to a World Bank study which he led five years ago which reached the same conclusion. "In state of the art projects three to five per cent of cost is spent on investigations but in India it is not even 0.5 per cent. People always say they have had geological surprises. They are surprises because they are not investigating. That is the biggest lesson that should be learned."

"I fully agree," says Bhati. "There is hardly any sufficient data available before the tendering process commences. We understand regarding areas which have the limitations like Himalayas wherein the cover above the TBM is as high as 1 to 2km. On the other hand, water transfer tunnel projects or metro projects have the accessibility of lands which clients want to cut short by not providing the proper information or doing proper geographical mapping which results in the award of the tender to the contractor as it is," he says. "The contractor in turn has to gather that information by himself which takes time therefore delaying the project and losing more time. Better and earlier information on geological details allows the manufacturers to design the machines and give them provisions to equip the machine to encounter all the problems in front."

One of the side effects of this is that projects are less attractive to international contractors who are not prepared to take the risks pushed onto the contractors under the design and build arrangements. "For the time being, due to aggressive local competition and actual contract versions comprising unacceptable risks for the contractor, we refrain from tendering for tunnel projects in India," a spokesperson for contractor Strabag told Tunnels and Tunnelling.

Yet ironically clients are demanding that international firms participate in main contracts. "Indian clients are putting a condition [in place] that the tunnelling manager must be an expert from outside of India," says Bhattacharya who says that the international financing provided to the metros also pushes for European consultants to be involved.

"It is true that they have more experience than us but the fact is that we are building experience. I have a team now running four TBMs simultaneously and now I am looking at Mumbai and Kolkata. We have the resources. Only problem is that the Indian companies don't have the technical credentials so they can't pass the technical bids so that is why we are making JVs."

However he says that this is changing and that for smaller bores of 1-2km Indian contractors are wining projects without international partners.

Another advantage that local firms have is their proximity to clients and their long term market positions which mean that local companies are more willing to accept delayed payments

## *Afcons turns to Sandvik DT820 jumbos for USD 250M road tunnel contracts*

Extreme conditions mean that the use of traditional tunnelling methods remains a vital in Indian tunnel construction. In early 2014 Mumbai based Afcons Infrastructure Limited received two further tunnelling contracts in Jammu and Kashmir from the National Highway Authority of India worth over USD 250M. Drill and blast was precluded from the outset with the road running through a wildlife sanctuary located at Nandini. Conventional drilling was needed and the Sandvik DT820 tunnelling drill jumbos have made light work of the tough operating conditions.

In the course of redeveloping the highway, around 150 bridges and numerous tunnels had to be built in the extremely inaccessible terrain of the Himalayas. Afcon's thus found itself facing quite special challenges in executing the project. First and foremost, the climatic conditions are extreme, varying from very high temperatures in the summer to pronouncedly low in the winter, with snowfalls and monsoon rains.

Over a length of 65km of the NH1 Highway between Jammu and Udhampur, Afcons was engaged in producing four twin tube tunnels with a total length of 1.5km each. The project that began in 2011 was completed in September 2014. At one point Afcons was three months ahead of what was an ambitious schedule.

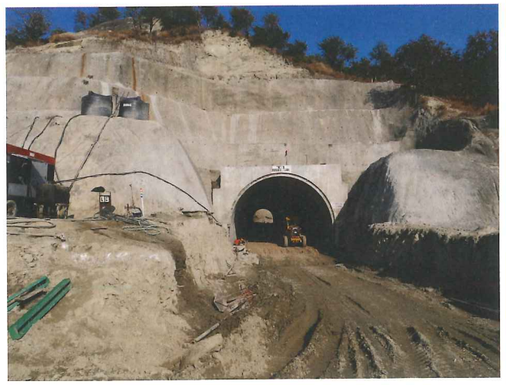
A major complexity on the project was the geology which was typical for the young Himalayan chain. Poor quality, broken rock with dolomitic limestone, and firestone lentils with high silicate content are mainly to be found. Rock class III to V, with strength of 60 to 100MPa and volume weight of 2,7t/m³, was prevalent. The RMR ranges from 40 to 60. The tricky ground conditions in particular made it necessary to have a reliable partner for securing the rock.

"The rock can collapse at any moment so that we must support the face quickly. We have a very reliable partner here with Sandvik," says Mihir Mishra, deputy general manager of Afcons Headquarters in Mumbai.

The design of the four twin tube tunnels (148m, 250m, 469m and 550m long), with a total length of approximately 1.5km each, was straightforward. The tunnels have a gap of 25 to 30m between them, and in the case of emergency, every tunnel can be used for evacuation. The tunnels were constructed by conventional mechanical cutting methods (NATM). The portals at the accesses to each tunnel are supported by steel arches over a length of 10m and are lined by placing a layer of wet shotcrete with steel fibre meshing.

Due to the operating requirements necessary due to the sensitive nature of the local environment (Nandini Nature Sanctuary) and inhabitants, a mandate to use conventional mechanical cutting methods (non-blasting operation) in tunnel excavation was imposed. This meant that at the face of the tunnel, the jumbo is used for drilling profile holes. The profile holes act as guiding lines for the mechanical cutting excavation; the 3m deep drill holes are created in order to be able to excavate the correct cross-section.

The actual excavation was done by different methods of mechanical cutting: roadheaders, drum cutter and vibro-ripper attachments. The resulting residue was loaded by excavator on large dumpers and then transported out of the tunnel.




***Afcons built four twin tube road tunnels each 1.5km long over a 65km length of highway with DT820s***

through claims. International firms however see this as too risky.

One way of reducing risk, says Bhati is to have the TBM manufacturer support the project through its life, not just at the beginning. "Most of the time delays are because manufacturers are not supporting the project and the contractor is not capable of coping with the difficult geology. On most of the jobs what we are doing we are supporting them on execution on a per metre basis," he says.

This strategy has been particularly important to the Bangalore metro for which delays have been widely reported in the local media. "Robbins was approached by the contractor to take over the contract but due to constraints of competitor's machine on the job, we declined the opportunity," says Bhati. "The project in Bangalore was delayed to the extent that client was looking to terminate the contract with the existing contractor. Robbins was then approached by the higher government officials of Bangalore metro seeking support for the project for the timely completion of the underground works for phase 1."

As a result Robbins supplied a crew along with materials and took over one of the drives of 750m in March 2015. To date 560m have been completed. The handover for the second machine is expected in January 2016. "The problems encountered inside the tunnel were that ground was challenging with very hard rock in a mixed face of hard rock and soft ground.

"The design of the machine is not robust to tackle such geology resulting in very low penetration rates thereby low advance rates."

Hard rock is also expected to be present beneath the streets of Mumbai where the next major metro project is about to get started.

### MUMBAI METRO LINE THREE

"On Mumbai Metro there are seven packages and we got package four," says Bhattacharya whose firm ITD Cementation are in joint venture with Continental Engineering Corporation of Taiwan and Tata Projects. Financial bids were opened in October and Tunnels and Tunnelling International understands that the client Mumbai Metro Railway Corporation is currently scrutinising the project budget which is lower than the forecast costs. One of the major issues which will be faced in the execution of metro tunnels in Mumbai city will certainly be the rock strata which will push up the tunnelling costs. The entire 32.5km line is underground.

"Geological survey suggests 90 per cent rock which will vary from 50 to 150MPa," says Bhati who has first-hand knowledge.

Although contracts are yet to be signed the low bidders have been revealed. Package one is India's biggest contractor Larsen & Toubro with China's Shanghai Tunnel Engineering Company. This JV has also achieved the lowest bid for package seven. Package two is expected to go to Russia's Moscow Metrostroy with local Hindustan Construction Company. Turkey's Dogus with local contractor Soma Enterprises is lowest on package three. Finally the low bidder for packages five and six is local J Kumar Infraprojects with China Railway No.3 Engineering Group.

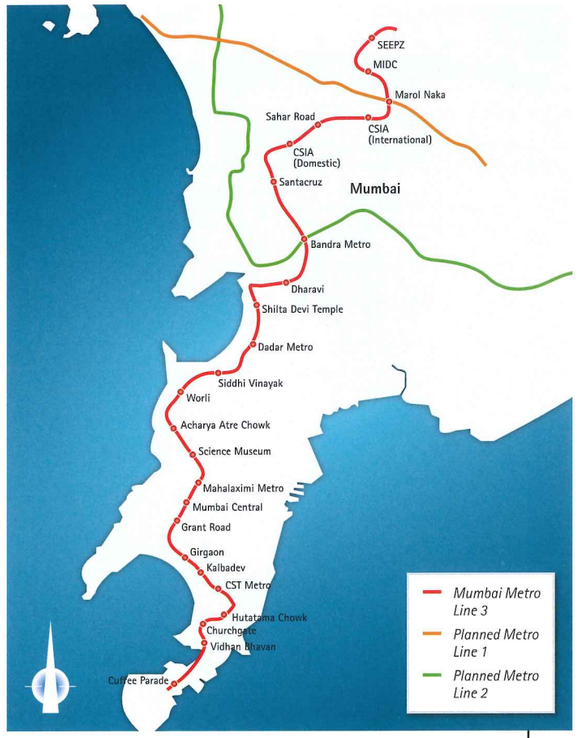
### OTHER METROS

Mumbai may be the next major project set for award but there are many more on the horizon. "Phase four of Delhi is coming with 90km of tunnelling. Bangalore phase one is about to complete and phase two is coming next year. Chennai phase three coming next year. Kolkata has another two underground packages coming," says Bhattacharya also pointing to forthcoming schemes in Lucknow in Uttar Pradesh, Hyderabad and Puna.

"The market is very promising perhaps one of the best in the world at this time, says Verman. "Now is the time that the country has to start moving into delivering infrastructure in difficult areas. Many projects are already sanctioned but procedures are such that they are not tumbling out in the way that we expected. However remain very optimistic. I am expecting 2016 to be a crowded year."

Data from the Timetric Construction Intelligence Centre places the value of work underway with a tunnelling element at USD 31bn however given the scale of projects planned – Verman says there are 3,000km of tunnels in the pipeline, the figure seems likely to rise substantially over the next five years. "I was involved in planning a railway through the Himalayas from Rishikesh to Karnaprayag, 125km long alignment of which 105km is in tunnels so that is the kind of project you are looking at and for this kind of distance you have to use TBMs, especially for the longer tunnels," he says.

Bhati of Robbins points to four main growth areas for the TBM tunnelling market. "We have hydropower projects in the pipeline which we see being awarded in 2016 and a couple of them will be using heavy provision of TBM. Then the metros like Mumbai which will be awarded in the next few months.




***Above:** Mumbai Metro route map with the three planned lines*

Bangalore and Chennai are planning phase two. Seeing the success of Delhi, Bangalore and Chennai everyone sees that it is the best solution possible. For the next 10-15 years one city after the other will keep having metros come up.," he says.

Water transfer tunnels to divert much needed resources is also a priority, as are road tunnels. "These are the future. People have realised that there is limited space available above ground so we have to go under. There is a 22km underground tunnel in Mumbai which is going to come from the southernmost part of the city through the coast to the airport. It is entirely underground and will be about 12m diameter. It was approved last month."

### LEARNING FROM THE PAST

Expectations are therefore high for India's growing and maturing tunnelling industry, but challenges remain and Verman urges government to learn from the past in terms of better planning and reducing bureaucracy so that contractors are able to get on and deliver. "There are huge projects coming forward and government should support this industry and nurture it because it is in the government's interest that these projects are built"

# DELHI METRO UPDATE

Delhi Metro project owner and operator Delhi Metro Railway Corporation (DMRC) gives *Tunnels and Tunnelling* an exclusive progress report on the networks third phase, as well as some lessons for its partners in the tunnelling industry

**DELHI METRO** is executing an MRT network of about 160 route kilometres in Phase Three which is a five year programme running from 2012 to 2017. Of the 160km over a quarter equivalent to 54km with 35 stations are underground. Out of the 54km route in underground sections, the length of single bored tunnel is 74.9km and rest of underground section/station is being built using cut and cover.

Tunnelling for Phase Three has involved 36 TBMs from eight manufacturers, with 26 of them working simultaneously at the project peak in July 2014 to create the 74.9km of bored tunnel. By December 2015 62.5km had been completed. The tunnelling works have been executed under 13 construction packages. To build the enormous expansion to the metro a total of 53,700 concrete segmental rings are required to line Phase Three, and manufacturing is almost complete.

The alignment has crossed below existing operational tunnels at three locations and passed beneath operational metro viaduct at six locations.

In addition, TBMs have crossed below the major vehicular outer and inner ring roads of Delhi at six locations, and below operational railway lines at two locations.

Like any major tunnelling scheme the project has met with challenges along the way. Line Six of the network, which was built during phase 2 of the project, is being extended northwards by 7km through the heritage zone of Old Delhi, running adjacent to historical monuments such as the Red Fort, Jama Masjid mosque and Kashmere Gate. Here the geology comprises a silt or silty clay layer overlaying medium to highly weathered rock, with occasionally

*Below: Work on contract CC20 of the Delhi Metro in 2014*

fractured and jointed hard quartzite at the lower levels, and with a water table at 10m below ground level. The alignment also overpasses the Phase One operating tunnels and was mined within 500mm of the foundation piles of an existing interchange station, with only 7mm settlement of the station structure recorded. The Jama Masjid to Delhi Gate station tunnel drives were originally planned with two TBMs. Due to the extremely hard rock experienced, progress of the first TBM was extremely slow with 39 interventions carried out to replace 204 single disc and 85 double disc cutting tools. Progress problems were compounded by a leaking bearing seal, and attempts to replace this met with limited success. It was therefore decided to deploy a third machine to drive from the opposite end at Delhi Gate station, and build a new retrieval shaft to lift all four TBMs. DMRC organised the evacuation and resettlement of 900 of the residents living along this area of Old Delhi, as the buildings were in various states of fragility, and vibrations from the rock tunnel drives, while within the allowable limit of 5mm/second, was considered too high a risk to the structures.

## LINE SEVEN

The new Line Seven in North West Delhi is an orbital route following the alignment of the Inner Ring Road, a major traffic arterial road circling the city. After departing from the Depot at the north west limit of this line, the alignment quickly changes to a three station underground stretch. The tunnels connecting the first of these stations, Azadpur, to the at grade ramp, cover a distance of 1,100m, and are at a depth of 21m at their low point. During tunnelling, both TBMs met with a large mass of intact rock which infringed the lower portion of the tunnel face and extended for approximately 30m. The TBMs used were both soft ground machines which had been used on a previous phase of the metro, and experienced high torque and overheating when attempting to cut through the rock zone. An attempt was made to break up the rock ahead of the cutter face by drilling and placing an expanding chemical to burst the rock and allow the cutter head to rotate and advance one ring at a time. The space within the chamber available to manage this exercise was very limited, and matters were made worse by the presence of wet running sand above the rock zone which dictated working under


*A joint venture of J. Kumar and CRTG at work on contract CC24*

compressed air.

To add to the challenge this section of Line Seven is planned to be open by the end of 2016 and progress is therefore critical to the overall programme. The advance being achieved in the rock was very limited, and a decision was made to deploy two additional TBMs equipped with suitable cutter heads to tackle the rock, from the planned receiving shaft, working back to meet the stranded TBMs; all four machines would be removed from a new rescue shaft. Preparations are currently in progress to start these drives in January of 2016.

## LINE EIGHT

In southern Delhi challenges were experienced along various stretches of Line Eight due to the presence of hard boulders located in a soft mica schist matrix. The boulders would often dislodge from the matrix after cutter face contact was made, and there was constant manual input required to break up or transfer these from the shield chamber.

In addition, the risk of grinding and movement of the boulders within the softer matrix often resulted in voided areas arising ahead of the cutter face with minor rock falls resulting from the filling of these voids.

Tight control of tunnelling was particularly required to review abnormal readings in the theoretical volume excavated, and cement slurry injection into the voided areas to lock the boulders in position and allow cutter head rotation and grinding of the rock proved to be successful.

On only one location along the alignment, a cavern became evident in the early stage of the drive east of Vasant Vihar station, with the space ahead and above the shield revealing a void which required 200m³ of cement/ fly ash mixture to be pumped in through the cutter head to infill the cavity before advancing the TBM. The full procedure is detailed in the box.

*Below: CC20 work well under way after initial land acquisition issues*

### *Line Eight 'critical zone' procedure*

On Line Eight in southern Delhi a particularly problematic zone was encountered by tunnellers (see text). The procedure used to overcome the zone was as follows:

1. The gaps between each consecutive spoke were covered by eight steel plates to prevent boulders from entering the chamber.
2. The chamber was filled with sand bags/ fly ash up to the level of the manlock. These sand bags helped to maintain an even pressure on the face. Also, the sand bag profile at the top was maintained in an inclined position so that grout did not fill the bulk head chamber.
3. After placing the sand bags, low strength grout (mixture of 700kg water, 350kg flyash, 100kg bentonite and 150kg cement per cubic meter of grout) was pumped through the shield ports. The strength of grout samples taken was less than 1Mpa, to prevent the grout from jamming the TBM cutter-head rotation and shield body. After the completion of first and second grouting the TBM cutter-head was turned slowly both clockwise and anti-clock wise direction per round.
4. After the grout was filled up to the manlock level the remaining space in the chamber was packed with sand bags
5. After the chamber was packed with sand bags again grouting was carried out, up to the vertex of the cutter head.
6. Finally the cavity above the TBM was filled by injecting grout material from the ports in the shield. This final grouting filled the void above the TBM till the pressure had built up to two bars and maintained for one minute.
7. Samples of the three mixes were collected during grouting to ascertain the setting-time, in order to gauge the time to restart-mining of the TBM.

## LESSONS IDENTIFIED BY DMRC

- The contractors should be pressured to carry out a more intensive soil investigation program at the start of the contract. As a minimum, probing at regular intervals, say 25m, to establish the presence of rock, should be carried out before TBM selection is accepted.
- There is a marked difference in the performance of TBMs from the range of manufacturers used for the project. The peak of 26 machines mining at any one time reflects the very high demand for equipment that had been expected from the outset. The client needed to be realistic in terms of his expectations, top of the range machines were unlikely to be available in numbers to satisfy the resource requirements of the project plan. Nevertheless, the versatility of the TBM to tackle varied ground conditions and it's track record before deployment certainly require very close scrutiny for any major project attempting to deliver to a tight timeline. A simple example is that certain machines allowed for the easy replacement of main bearing seals within the tunnel, others failed to successfully carry out this work.
- The joint ventures selected for the works should be closely examined for their international exposure. There have been examples on Phase Three of international partners failing to perform to expectations due to lack of experience in contracting in overseas environments.
- Do not overlook the challenges of cross passages. If NFPA 130 is used as the guideline for tunnel safety, the number of passages can be large; there are over 140 required for Phase Three. The need for experienced mining personnel to manage the ground treatment, excavation and lining works in areas with soft, wet ground is paramount, and the time frame for executing these works can easily delay ongoing services installation, including track laying, in the tunnels

# FARNWORTH ENLARGED AND ELECTRIFIED

## *TBM specifications*

**Shield:**
Outside diameter: 8,900m
Overall length: 5,600mm

**Shove rams:**
Number: 20
Capacity (each): 105t
Stroke: 1,800mm

**Face rams:**
Number: 4
Capacity (each): 80t
Stroke: 1,000mm

**Cutter booms:**
Power (each): 110kW
Lift rams: 2 no. 40t
Telescopic ram: 1 no. 40t
Bucket ram: 1 no. 40t

Work to upgrade the Farnworth Tunnel as part of a route electrification project called for tunnel enlargement works, and led to the procurement of a UK-manufactured TBM. **Ian Clarke**, writing for the manufacturer, reports

TUNNEL ENGINEERING Services (TES) recently provided a specially designed tunnel boring machine (TBM) in support of the Network Rail route electrification project between Manchester and Preston via Bolton which when completed will electrify one of the North West's busiest routes and allow faster trains with more passenger space.

As part of the construction works there was a requirement to reconstruct/enlarge the Farnworth Tunnel which is on the line about 4km southeast of Bolton. The reconstruction was required because the original tunnel size would not allow the installation of the new overhead power lines required by the new trains.

As well as the tunnel rebuild, some 1,600m of track through the area also had to be lowered to ensure smooth running of the electrified rail line.





## CHALLENGES

The original tunnel was constructed in the mid-1830s and runs over a length of some 270m. The construction comprises a mix of brick and stone lining with stone portals through a mix of ground conditions.

Prior to the electrification reconstruction works commencing, over 1,500 ground investigation bores were made to establish what ground types would need to be handled by the tunnelling machine during the excavation operation.

After examining the market, TES was approached as the potential TBM manufacturer with a brief to design what ultimately proved to be the largest TBM ever constructed in the UK.

The TBM, named Fillie, had to bore a new 270m-long tunnel, removing some 30,000t of material and install 1,940 concrete lining segments to complete the new tunnel. Work started at the site in March 2015 in preparation for the arrival of the TBM.

*Both:* ***The project to improve the line involved upgrading a tunnel built in the mid-1830s***

Prior to works starting, construction of the TBM itself was something of a challenge. Having to excavate the original tunnel with its Victorian interlocked solid stone work, brick lining and the surrounding ground meant that the design had to be not only durable to enable the very hard stone work to be removed but also flexible enough to enable excavation unit changes relatively quickly and easily as the ground

conditions changed during the tunnel advance.

The location and proposed route of the new Farnworth Tunnel was such that it effectively required the removal of pretty much all of the existing tunnel alignment and also required the excavation for the new tunnel to, at times, pass very close to the original smaller diameter Farnworth (running) Tunnel that was built in the early 1830s.

Because of these proximities it was decided that a full face TBM would not be appropriate for this drive. After careful consideration of the predicted conditions both for ground and tunnelling works, TES, in co-operation with the team from tunnelling contractor J. Murphy & Sons ultimately designed the 9m outside diameter open face shield, with leading edge 'forepoling' boards for initial ground support at the face, that utilised centrally-mounted twin mining booms that could each carry a roadheader drum cutter and/or a bucket excavator. In the event, despite not having been initially designed for this use, ground conditions meant that booms were also utilised with a combination of hydraulic breaker and bucket depending on the ground type encountered.

TES received the first enquiry about a possible tunnelling machine from Murphy in November, 2014. The initial brief was that the machine would need to handle foam concrete, solid stone brick and what was believed to be softer ground types along the tunnel bore route. In barely one month an initial design for the excavator-based TBM was presented and Murphy agreed to proceed, provided the unit was ready to be on site no later than July 2015.

In just seven months, by July 2015 TES had completed the design, built and completed testing on the shield section of the tunnelling machine. By the end of July, whilst TES was finalising testing of the segment lining erector in the yard, engineers from Murphy were dismantling the front end of the shield alongside TES engineers for transport to site. The complete unit was ultimately dismantled at the TES yard in just two days. At the Farnworth Tunnel site, in association with TES engineers, Murphy rebuilt the whole machine in just five days. The machine commenced tunnelling immediately on completion of the build.

## TUNNELLING WORKS

Whilst the machine was under construction, from March 2015, Murphy had commenced preparation works with the construction of the launch portal for the TBM and filled the old tunnel from end to end completely with 7,500m³ of foam concrete. This was intended to provide support to the old tunnel and surrounding ground as it was excavated. Despite

*Below: **Crane manoeuvres TBM components into place***








the more than 1,500 test holes drilled to investigate the ground conditions, the drive actually encountered far more sand than was predicted.

The excavation removed all of the old tunnel, upsizing the diameter by some 2 to 3m to 9m o.d. The route ran mostly on the line of the old tunnel which included an existing curve. The new tunnel curve however was not as tight as the old one to allow the new route to handle the newer trains. However, the new tunnel route passed very close to the alignment of the Farnworth (running) Tunnel, passing by with as little as 2m clearance at times.

As well as removing the old tunnel, the new route also required the invert of the old tunnel to be excavated because the upsizing of the existing tunnel was confined vertically due to limited ground cover over the drive. However, once the new track is completed the track horizon is not expected to be much lower than the old track.

At the start of tunnelling works the excavator booms were fitted with roadheader drum cutters which were used to cut through the old tunnel headwall. The high stone strength caused significant vibrations when cutting which meant that the use of the drum cutters had to be limited. So, once sufficient of the headwall was removed it was decided to exchange the drum cutters for hydraulic pick units or peckers to limit the impact of excavation vibrations on the machine structure. Whilst the original TBM design did not take into account use of peckers, the interchange was made possible with minor modifications so the tunnelling process could proceed. However ground conditions deteriorated into running sand at times which caused delays as Murphy had to inject ground stabilisation resins ahead of the face.

This was also a necessity where the tunnel ran beneath the alignment of the A666 road. As the tunnel passed beneath the road, the surface experienced some anticipated subsidence. However plans had been put into place should this occur and the road was resurfaced back to its original level during an overnight operation with minimal, if any, disruption to this busy traffic route.

It proved possible to safely excavate while concurrently installing and grouting sections of the tunnel wall as was originally planned. At one other point in the excavation a running sand inrush occurred with some 100t of sand burying the machine face. This caused a further delay as the site had to be open cut using a shaft to re-stabilise the ground over the TBM face. However the remedial works worked very well and despite the ground problems the TBM completed the new 270m tunnel on 30 October 2015. Commenting on the project from the TBM manufacturer's viewpoint Geoff Clarke, managing director of TES said: "This perhaps is one for our own record books. From the date of the first enquiry back in November 2014, through design, build, test, delivery, commissioning, tunnelling, holing and scrapping of the TBM at the end of the project, the whole thing was completed in less than 12 months from start to finish. This was despite the fact that as far as we know this is the largest tunnelling machine built to date in the UK. This was an excellent job all-round in the time frame available and it was only possible due to the time and effort of our TES team working in complete concert with the Murphy team over the whole project duration. This was not always the smoothest running project but it does show what British engineering can really achieve when it needs to."

The new section of electrified rail line was operational in December 2015

*Above: **Excavation work with the hydraulic boom***

*Below: **Worksite location next to operational rail***

# CONQUERING COBBLY, BOULDERY GROUND

***Steve Hunt***
Steve is a senior tunnelling technologist at CH2M based in Henderson, Nevada

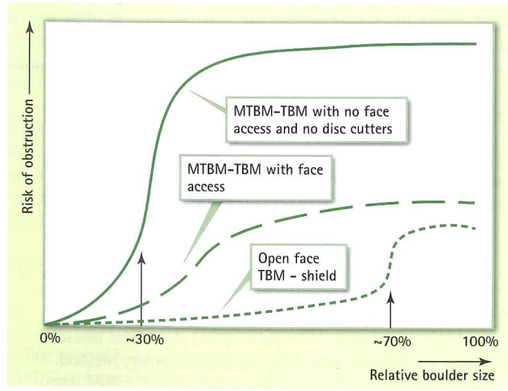
Properly managing risk of tunnelling in cobbly, bouldery ground can be accomplished using four steps. **Steve Hunt** of CH2M, explains the relevant investigations, baselines and mitigation methods

TUNNELLING IN ground with cobbles and boulders involves risks. Primary risks include: obstruction; reduced advance rates; steering difficulties; increased risk of excessive lost ground settlements or sinkholes and associated damage; impact or vibration damage to cutter housings or TBM gears; increased abrasion and wear of cutters, cutterhead and mucking system; and lower utilisation resulting from intervention time to remove obstructions and repair worn tunnelling components. The importance of these risks depends on the extent of cobbly-bouldery ground and the tunnelling means and methods employed. Assessment of risk severity requires specialised subsurface investigation, identification of potential hazards, quantification of probability of occurrence and potential consequences. Once risk severity has been determined, mitigation measures can be selected and implemented.

In order to properly manage risks of tunnelling in ground with cobbles and boulders, four steps should be followed:

1. Understand the risks – identify the ground hazards and associated potential consequences for the tunnelling methods being considered.
2. Characterise and quantify – use special subsurface investigation methods to collect ground condition data; characterise the cobble, boulder and matrix conditions; quantify volume ratios, sizes, shapes, distributions, abrasivity and rock clast strengths.
3. List hazards, potential consequences and resulting risks - use a risk register to thoroughly identify and quantity the risks.
4. Determine mitigation methods – list mitigation options and work with prospective contractors and the owner to determine how best to mitigate the unacceptable risks through prescriptive specifications, baselining, payment items and construction administration.

*Below: **Figure 1, Risk of boulder obstruction***




## UNDERSTANDING RISKS

Tunnelling risks are not only dependent on the ground conditions, but also on the site conditions and tunnelling methods employed. Site condition factors include: tunnel depth; surface access constraints (land use and easement restrictions); utility interferences to potential rescue or obstruction removal shafts; dewatering and ground improvement limits; settlement limits; vibration limits and ground contamination. Tunnelling method factors involve: tunnel size and shape; face stability control measures (open mode vs. closed and pressurised mode); required ground improvement; excavation tools (TBM cutters, spades, backhoes, rotary milling heads, etc.); available power; face access; and the mucking system.

In general, cobble and boulder impact risks are less for large tunnels with free air (open-mode) access and higher for smaller tunnels with pressurised face (closed-mode) access. This concept relative to obstruction risk is illustrated in Figure 1.

Many hazards and potential consequences are listed in Table 1. Quantification of the potential consequences in terms of safety, cost or delay is much more difficult and depends on specific ground and site conditions. Some of the more common severe consequences include: obstructed advance (stuck TBM) requiring an abandoned tunnel drive or rescue shaft or hyperbaric intervention; severe cutter, cutterhead, mucking system or gear damage from impacts or abrasion resulting in a need for a rescue shaft or hyperbaric intervention to make major repairs; and much slower than anticipated advance rates or maintenance delays that result in much longer tunnelling time and costs.

## INVESTIGATE, CHARACTERISE AND BASELINE

Managing risks of tunnelling in cobbles and boulders requires an adequate understanding of ground conditions and the geologic setting. Too often, the site and subsurface investigation program

*Table 1. Boulder encounter hazards and potential consequences for TBM excavated tunnels*

| Hazard or Condition | Potential consequence |
|---|---|
| Boulder(s) over ~ 20-30 per cent diameter, no face-chamber access or disc cutters | Stuck TBM, rescue shaft or shaft-tunnel required or TBM-tunnel abandoned |
| Boulders composed of much harder, stronger rock than expected | Severe pump and slurry line wear resulting in pump failure or line rupture |
| Cobble and boulder quantities much greater than expected | Severe cutter wear, higher tool replacement cost, potential stuck TBM |
| Matrix ground or cobbles and boulders are much more abrasive than anticipated | Severe mucking system wear resulting in stoppages for repair or replacement |
| Boulders in weak-loose matrix resulting in plucked boulder rolling on cutterhead | Severe cutterhead wear or rock crusher bar wear, reduced advance rate, stuck TBM |
| Mixed face heading weak soil zone adjacent to hard bouldery ground | Steering difficulty, TBM shield deflected beyond line or grade limits |
| Advance rate higher than allowed for disc cutters causing plucked rock | Broken cutters or cutter housings and or cutter arms or damaged gears from high impact forces |
| Plucked boulders extending beyond perimeter or at face result in voids and ground loss | Perimeter voids, excess lost ground, sinkholes, damaging settlements |
| Perimeter boulder(s) not cut by gage cutters or plucked from perimeter | Pipe or lining damage from passed perimeter boulder causing high contact stresses |
| Attempt to blast or split boulders at heading in free air and unstable soil | Face instability and excess ground loss at face resulting damaging settlements or sinkholes |
| Large oblong boulders pass through cutterhead opening | Boulders jam inside rock crusher or excavation chamber requiring an intervention to remove |

*Source: Author*

is not customised to provide suitable information on cobble and boulder conditions. In most cases, a routine subsurface investigation program will not provide the information needed. What is needed is a geologic desk study followed by a customised, phased, subsurface investigation program where each phase is evaluated in a geologic setting and the next phase is designed to reduce remaining uncertainties. All the relevant collected data should be presented in a geotechnical data report (GDR). Key cobble, boulder and matrix ground conditions should be baselined in a geotechnical baseline report (GBR).

## Geologic desk study and setting

An investigation of cobble and boulder conditions should be completed in the context of a geologic setting to be effective. The occurrence of cobbles and boulders is dependent on geologic processes, which affect the character of geologic units. As a result, different geologic units tend to have characteristic ranges in cobble and boulder conditions. Each geologic unit should be specifically baselined and as a result, the subsurface investigation program should be designed to help define geologic units.

A site reconnaissance and geologic desk study should be completed to determine to scope of the initial subsurface investigation phase. The desk study should obtain and include review of available: geologic maps, reports and papers; previous subsurface investigation reports from any source in the vicinity; a Phase 1 Environmental Site Assessment; a geologic site reconnaissance, an initial phase subsurface utility study; and a review of reports from previous underground construction projects in the project vicinity. This information should be evaluated to establish an initial geologic setting and a crude risk register (at least a list of potential hazards and risks). The scope of the first phase of subsurface investigation should be designed to verify the interpreted geologic conditions, the desk study information and to reduce specific uncertainties.

## Subsurface investigation

A subsurface investigation program that includes assessment of cobble and boulder conditions should be phased and should include multiple exploration methods. After each phase, the geologic setting should be refined and remaining uncertainties for the anticipated underground construction methods identified. The subsequent phase should be designed to reduce uncertainties and improve geologic condition reliability.

Conventional 100 to 200mm diameter rotary wash or hollow stem auger borings with split spoon sampling is rarely adequate alone for investigation of cobble and boulder conditions. Conventional borings and sampling should be completed and can be enhanced by drilling observations such as determination of 'relative drilling resistance' as defined in Hunt (2014).

In most cases, conventional borings should be supplemented by subsurface investigation methods. The effectiveness and relative cost of 10 subsurface investigation methods was discussed in Hunt and Del Nero (2010) and is discussed in more detail in Hunt (2014). The most cost-effective additional method is often rotosonic coring. It allows continuous coring and sampling. Cobble and boulder sizes and quantities can be determined by careful logging of core samples and extrapolation of sizes from pieces in the core. A study of various exploration methods within glacial soils in Columbus, Ohio, (Frank & Chapman 2001) also found rotosonic coring to be the most cost- effective supplementary method.

Other methods that should be considered and utilised when







practical include: test pits (particularly when the tunnel zone geologic unit can be reached); accessible construction excavations, shafts or quarries; Becker percussion borings; and large diameter auger borings. Generally less effective methods include cone penetrometer probes, cross-hole and surface seismic refraction, and ground penetrating radar.

Another potentially very effective method to consider is horizontal directional drilling or directional-horizontal boring with coring capability. This method can result in much more sample recovery from the proposed tunnel zone and therefore better baselining of cobble and boulder conditions.

## Cobble and boulder baselining

Cobble and boulder conditions can and should be baselined for most tunnel projects even where pressurised face tunnelling results in very little or no access to the heading to determine actual ground conditions encountered for comparison to baselines. Despite challenges in measuring cobble and boulder conditions encountered, baselines are still essential to help bidders understand anticipated conditions and better manage risks by selecting suitable means and methods, estimating reasonable advance rates and planning mitigation costs. The primary cobble and boulder (rock clast in soil matrix) related conditions to consider baselining include:

- Quantities and size ranges for anticipated cobbles
- Quantities and size ranges for anticipated boulders
- Cobble, boulder distributions and concentrations along tunnel (isolated vs. clustered) for each geologic unit
- Rock clast mineralogy and rock type descriptions including both native and erratic clasts
- Rock clast unconfined compressive strength ranges (histogram)
- Cerchar abrasivity index (CAI) ranges for rock clasts
- Soil matrix types, strength (including degree cemented), density, abrasivity and permeability.

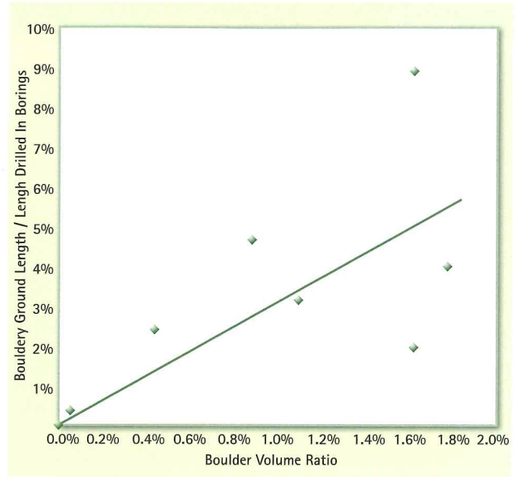
Additional conditions to consider baselining include: cobble and boulder angularity and shapes. Cobble and boulder quantities are generally best baselined as boulders per length of tunnel for each selected size range, however cobble and boulder volume ratios for geologic units should also be given. Other items require baselining of ranges and mean-averages. When sufficient data exists, histograms are generally the best method of baselining. Histograms show both the data range and predominant values.

The thoroughness of the subsurface investigation program (available data) and risks involved should guide decisions on how many of these items to baseline. Where data from a site specific subsurface investigation program is lacking, regional typical value data obtained from the desktop study might be used. For example, if data from other projects or from geologic studies of similar rock types indicates typical unconfined compressive strengths range from 135 to 200 MPa, and site specific data is lacking, the typical local values should be baselined.

Regarding cobble and boulder quantities, ultimately, bidders want to know baseline quantities for expected size ranges. If the excavated tunnel diameter is known, the quantities for selected size ranges along each tunnel reach can be baselined. Alternatively, cobble volume ratio (CVR) and boulder volume ratio (BVR) can be baselined for anticipated geologic units or tunnel reaches.

## Volume ratio baselining

Volume ratio methods involve analysis of geologic and subsurface investigation data to determine CVR and BVR values for specific geologic units. The data can often include a percentage per length drilled in cobbly-bouldery ground within conventional borings and CVR-BVR determinations from a second source such as rotosonic cores, test pits, or large diameter auger bores.




*Above: **Figure 2, BVR vs. per cent bouldery ground in borings (Hunt, 2002)***

To improve interpretation of conventional small diameter borings, the author developed a BVR correlation chart using cobble and boulder indications such as high Standard Penetration Test (STP) blow counts, Relative Drilling Resistance (RDR) - (Hunt & Angulo, 1999; Hunt, 2002; Hunt & Del Nero, 2010; Hunt 2014). Figure 2 shows the correlation between small diameter conventional boring indication of boulders and BVR. Tables 2 and 3 (page 40) provide charts for RDR and STP for use in indicating cobble and boulder occurrence.

An interpretation of the data and determination of the ratio between CVR and BVR is also needed for each geologic unit. CVRs are generally higher than BVRs. For several Milwaukee projects studied, cobble volume ratios were estimated to be approximately one-and-a-half to two times the BVRs, which resulted in much higher cobble quantities due to their smaller sizes. On the Bradshaw 8 project in Sacramento, California, the CVRs ranged from 25 to 50 per cent and were much greater than BVRs due to fluvial sorting – CVRs typically ranged from five to 10 times greater than the BVRs. On two other projects in California, CVRs ranged from three to five times the BVRs. On the Chengdu Metro project in China, CVRs ranged from 60 to 85 per cent in some geologic units. On the BWARI project in Columbus, Ohio, a back analysis by the author indicated an approximate CVR of 0.22 per cent and a BVR of 0.34 per cent - a ratio of 0.65 to 1.

Estimated total average CVR to BVR ratios for 23 projects studied vary from approximately 0.5 to 10 with an average of about 2.

Once a percentage of cobbly and

*Table 2. Relative drilling resistance (RDR)*

| RDR | Term | Criteria | Typical ground conditions |
|---|---|---|---|
| 1 | Very easy | No chatter, very little resistance, very fast and steady drill advance rate | Very soft to soft silts and clays; very loose to loose silts and sands; no gravel, cobbles, boulders or rubble |
| 2 | Easy | No chatter, some resistance, fast and steady drill advance rate | Firm to stiff silts and clays; loose to medium dense silts and sands; little or no gravel, no to very few cobbles, boulders or pieces of rubble |
| 3 | Moderate | Some chatter, firm drill resistance with moderate advance rate | Stiff to very stiff silts and clays; dense silts and sands; medium dense sands and gravel; occasional cobbles or rubble pieces (2-3 occurrences per 10 ft) |
| 4 | Hard | Frequent chatter and variable drill resistance, slow advance rate | Very stiff to hard silts and clays with some gravel and cobbles; very dense to extremely dense silts and sands with some gravel; dense to very dense sands and gravel; very weathered, soft bedrock; frequent cobbles and boulders or rubble pieces (3-4 per 10 ft) |
| 5 | Very hard | Constant chatter, variable and very slow drill advance, nearly refusal | Hard to very hard silts and clays with some gravel; very dense to extremely dense gravelly sand or sandy gravel; very frequent cobbles and boulders (at least 5 per 10 feet); weathered, very jointed bedrock |

*Source: Author*

bouldery ground per unit boring length for each geologic unit is determined from conventional borings, CVRs and BVRs can be estimated for each geologic unit using Figure 2. The resulting estimates should be compared to CVR and BVR date from the other subsurface exploration sources as well as data from previous shaft and tunnel excavations in the same geologic units. Any inconsistencies should be rectified if possible, but ultimately the more reliable and often the more conservative interpretations are used.

Specific quantities of cobbles and boulders can be estimated for shaft and tunnel excavation volumes in each geologic unit using a spreadsheet. The size ranges desired and maximum anticipated boulder size must first be selected. Figure 3 shows BVR data evaluation completed for a tunnel reach using a negative exponential distribution function within a spreadsheet. Subsurface investigation data analysis is used to estimate the mean size and standard deviation for each tunnel reach in a geologic unit. An "area factor" calculation is completed to convert computed boulder volumes into boulder quantities for each size range. The result is an estimate of the total number of boulders for the reach being analysed. The resulting boulder quantities can then be baselined.

### Probabilistic methods

Attempts to predict boulder quantities using statistical or probabilistic methods date back to at least 1976 when Stoll 1976 attempted to use a random probabilistic method. Tang & Quek 1986 published the results from a statistical evaluation of the lengths of boulders taken from boreholes in sedimentary deposits in Singapore. They showed a statistical correlation of lengths in boreholes with excavated boulder sizes. Probabilistic methods were also used for the Storebaelt Tunnel in Denmark (Ditlevsen 1997, 2006) and more recently for a tunnel in Italy (Felletti 2009).

The most extensive study of subsurface exploration for tunnelling in bouldery ground and development of an approach to predict boulder quantities and sizes for baselining was completed by Frank & Chapman during the early to mid-2000s for the BWARI project in Columbus, Ohio. They developed an exponential distribution relationship similar to that used for the Storebaelt Tunnel. The number of clasts (boulders) expected is computed as N=C/V•d where: N = no. clasts, V = volume excavated, C is a constant correlated with sample size data, and d is a constant correlated with clast size distribution (Frank & Chapman, 2005). The method requires a significant amount of reliable sample data from the subsurface investigation. The constant d is evaluated from boulder sizes found in the investigation. The constant C is calculated from boulder volume data. The number of clasts for selected sizes is then computed using the formula with these constants. Tunnelling results indicated that boulder quantities were slightly over-predicted, but accurate estimates of actual boulders encountered were difficult to make from the broken rock and very large quantities of muck.

### Baselining conclusions

Which aspects of cobble and boulder conditions to baseline and whether or not to directly baseline conditions or use functional baselines depends on the ground conditions, anticipated methods of construction and project owner's preference for risk sharing. The method to use for evaluating data to predict quantities for baselining should depend on the size of the project and the quality and quantity of data available. When desired to baseline quantities,

*Table 3. Standard penetration test (STP)*

| Approximate average relative density of soil matrix | Corrected N value indicating probable cobbles and or boulders (blows/ft) |
|---|---|
| Loose | >25 |
| Medium dense | >50 |
| Dense | >75 |
| Very dense | >100 |

*Source: Author*







**Project** Example at BVR =1% **Drive** 1000 ft of 10 ft ED tunnel

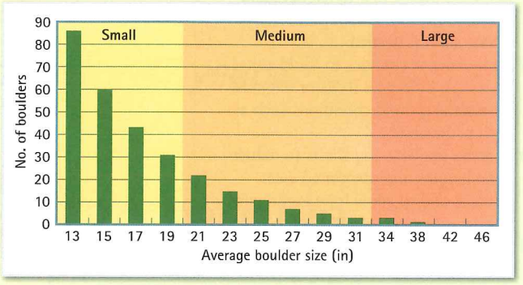
Tunnel excavated volume, $T_t$ = 78500 ft³
% boulders by volume, BVR = 1.00%
ED = 120 in
ED = 10.00 ft
L = 1000 ft

Total volume of boulders, $V_B$ = 785 ft³
Mean value, $\sigma$ = 18 in
Standard deviation, $\delta$ = 10 in

| Lower bound [in] | Upper bound [in] | Avg boulder size [in] | Area factor | Vol. of boulders ft³ | Single boulder vol*, ft³ | Number of boulders |
|---|---|---|---|---|---|---|
| 12 | 14 | 13 | 0.141 | 76 | 0.890 | 86 |
| 14 | 16 | 15 | 0.152 | 83 | 1.367 | 60 |
| 16 | 18 | 17 | 0.159 | 86 | 1.990 | 43 |
| 18 | 20 | 19 | 0.159 | 86 | 2.779 | 31 |
| 20 | 22 | 21 | 0.152 | 83 | 3.752 | 22 |
| 22 | 24 | 23 | 0.141 | 76 | 4.929 | 15 |
| 24 | 26 | 25 | 0.125 | 68 | 6.330 | 11 |
| 26 | 28 | 27 | 0.106 | 58 | 7.973 | 7 |
| 28 | 30 | 29 | 0.087 | 47 | 9.880 | 5 |
| 30 | 32 | 31 | 0.069 | 37 | 12.068 | 3 |
| 32 | 36 | 34 | 0.090 | 49 | 15.922 | 3 |
| 36 | 40 | 38 | 0.044 | 24 | 22.228 | 1 |
| 40 | 44 | 42 | 0.018 | 10 | 30.013 | 0 |
| 44 | 48 | 46 | 0.007 | 4 | 39.430 | 0 |
| | | | 1.448794 | 785 | Total | 288 |

Avg B/ft = 0.3
Avg B size*,d = 1.5 ft
Avg B size*,d = 18 in
Avg B vol = 273 ft³
Avg B vol = 0.101 yd³

Small boulders = 220
Med boulders = 63
Large boulders = 5
Small boulders = 331 ft³ 12.2 yd³
Med boulders = 368 ft³ 13.6 yd³
Large boulders = 86 ft³ 3.2 yd³
Total voloume = 785 ft³ 29 yd³




| r=d/2 | Size, d(ft) | Boulder volume | |
|---|---|---|---|
| sphere = 1.33πr³ | 1 | 0.52 ft³ | 0.019 yd³ |
| cube = d³ | 1 | 1.00 ft³ | 0.037 yd³ |
| *rd'd cube = 0.7d³ | 1 | 0.70 ft³ | 0.026 yd³ |
| rd'd cube = 0.8d³ | 1 | 0.80 ft³ | 0.030 yd³ |

the CVR and BVR method is generally more practical than probabilistic methods for most projects. Probabilistic methods are viable for larger projects with a significant amount of quality data. In either case, the method should consider the geologic setting, geologic variability and local experience.

## HAZARDS, POTENTIAL CONSEQUENCES AND RESULTING RISKS

The occurrence of cobbles and boulders creates a large variety of hazards that may result in concernable risk depending on the ground conditions, surface conditions and tunnelling method. In general, these risks can be grouped into three categories: obstruction, abrasion and impact vibration. Hunt 2014 provides a detailed discussion of these risks. This is a general overview.

### Obstruction risk

Obstruction risks are those that may obstruct or stop the tunnel advance, significantly slow the rate of advance or result in steering problems. A large boulder or clusters of cobbles and boulders may stop tunnel advance if the energy required to break and ingest the rock clasts exceeds the capabilities of the TBM and cutters. TBM obstruction and advance rate reduction are very common tunnelling risks (Hunt and Mazhar 2004).

### Abrasion risk

Abrasion risks are related to wear or breakage of components that come into contact with the ground and muck including: cutters, cutterhead, crusher and mucking system. The occurrence of cobbles and boulders can significantly increase the rate of abrasion of components beyond that caused by the abrasiveness of the matrix soil (Gharahbagh et. al. 2012). The increase is dependent on the abrasiveness of the cobble and boulder rock clasts and the CVR and BVR magnitudes.

### Impact risk

Excavating and ingesting cobbles and boulders causes impact forces and vibrations. Impacts tend to cause cutter and cutter housing breakage and may cause cutter bearing or gear-pinion failures. The risk of impact consequences increases with boulder size and CVR and BVR magnitudes. Impact forces also tend to be more severe when the difference in density and strength between the rock clasts and matrix are more extreme, such as when cobbles and boulders are in a loose, soft matrix.

***Above: Figure 3, Boulder size distribution for anticipated BVR value***

### Risk assessment

Hazards and potential consequences from encountering anticipated cobble and boulder conditions for each tunnelling method being considered should be analysed using a risk register. This form of risk assessment requires reliable data on cobble and boulder conditions from a thorough, phased subsurface investigation program and tunnelling experience provided by engineers, contractors and TBM manufacturers. Once risk levels have been determined, risk allocation and mitigation measures can be determined.

## MITIGATION METHODS

When assessment indicates high, unacceptable tunnelling risks from cobbles and boulders, they should be avoided, mitigated or allocated. Avoidance and mitigation measures generally involve both planning and design decisions and construction actions

Significant cobble and boulder risk avoidance and mitigation may occur during planning and design. Reliable data on anticipated cobble and boulder ground conditions and tunnelling methods is required. Planning and design

phase avoidance and mitigation measures may include:

- Vertical and horizontal alignment changes to avoid or minimise extent of tunnelling in adversarial ground conditions.
- Horizontal alignment changes to minimise overhead interferences and obstructions that would prevent a rescue shaft if needed.
- Tunnel depth changes to avoid zones with high CVRs and BVRs or minimise adversarial ground conditions such as high permeability.
- Spacing and locating shafts to reduce drive lengths and associated wear impacts and to allow for easier repairs and maintenance of TBM components.
- Spacing and locating ground improvement 'safe zones' to allow open mode interventions for cutter changes and cutterhead repairs.
- Increasing the allowable or specified tunnel diameter to improve potential TBM power, face access and intervention options.
- Use of prescriptive specifications to require bidders-contractors to have minimum essential TBM system components. This might involve: cutter types; cutterhead armouring and opening ratio restrictions; excavation chamber access; requirements for hyperbaric intervention, TBM torque-speed, and or conditioning or slurry to minimise abrasion; TBM type restrictions, purpose-build TBMs vs. refurbished TBM, advance probing and grouting from TBM requirements, and more.

Depending on specification requirements, contractors and TBM manufactures have a considerable to full range of potential mitigation measures to manage cobble and boulder risks. Again, reliable data on anticipated cobble and boulder ground conditions is essential to allow effective construction phase risk mitigation. Contractors and TBM manufactures have the most control over TBM robustness and components to eliminate or resist cobble and boulder impacts. These measures have a cost that must be managed through bidding, pay items and contractor controlled risk management. Some of the contractor and TBM manufacture cobble and boulder risk mitigation measure options are:

- TBM type and component design: cutter types, cutter access, excavation access, cutterhead and mucking system materials and armouring, grizzly bars, rock crusher, EPB screw design, face access, air locks, etc.
- TBM and mucking system operation measures: advance rates, cutterhead rotation speed-torque, conditioner use, slurry design, and advance probing and grouting capability.
- Shaft spacing and locations affecting drive lengths including additional shafts or safe zones for interventions.
- Frequency of inspection and maintenance activities.

## SUMMARY AND CONCLUSIONS

During the past 20 years, the tunnelling industry has made considerable improvements in capability to successfully microtunnel and tunnel in cobbly-bouldery ground. Subsurface investigations have gotten more varied and focused to obtain necessary data. A database of typical cobble and boulder volume ratios for common soil types has grown. Designers have developed practical and statistical methods to predict cobble and boulder occurrences. These methods have been used with success on many projects. Baselining and pay items (where applicable) have helped to significantly reduce contractual and cost risk of excavating through cobbly-bouldery ground. Risk management methods should be used to assess cobble and boulder risks along all portions of the alignment. Where the consequences of getting stuck are high or where the cost of interventions to change cutters is excessive, contract documents might require more robust TBMs or MTBMs with face access and combination roller and scraper cutters. Where conditions are bad and risks are high, redundancy and backup plans should be designed with appropriate pay items to manage uncertainties and risks

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# COST EFFECTIVE SMALL BORE

*Excavation of an industrial tunnel in Pilsen*







**Tomas Zitko** of Czech engineering company *Sudop Praha* looks cost-efficient methods of constructing smaller diameter tunnels, specifically methods that are prevalent in the Czech Republic. At the time of writing, **Zitko** was at *Pohl*, a specialist in the excavation of small-diameter tunnels for utilities, and also tunnels that are required as ancillary structures on large tunnel projects, such as emergency cross passages for highway tunnels or ventilation or utility tunnels

SMALL BORE TUNNELS are sometimes required on projects that more prominently feature a large diameter tunnel. The author has noticed that, when in the hands of contractors and designers more accustomed to large diameters, these structures are proposed using more expensive methods than are commonly used in the microtunnelling industry. This article deals with three methods commonly-used in the Czech Republic that do not rely on the use of sprayed concrete or expensive and sophisticated construction equipment. These are:

- Excavation of trapezoidal tunnels using an initial support of steel mine frames and UNION lagging (UNION is a type of steel sheet well known in Central Europe)
- "Prague Frames," a hand tunnelling support method that is common within the Czech Republic. This comprises an egg-shaped tunnel supported by a steel flat bars and steel/beech lagging
- Man shield pipe jacking using a simple unadorned jack and a plain steel sleeve

***Tomas Zitko***
Tomas is a tunnel designer for the Czech construction company Sudop Praha

## SHAFT CONSTRUCTION

Shaft construction is frequently required on a project prior to other tunnelling works to provide access. In the Czech Republic similar methods are used to provide initial support for shafts and for tunnels.

If the shafts are just for temporary purposes, the dimensions depend solely on the usage requirements, so an approximate size of 2.3 × 2.8m is generally used. This type of shaft can be supported by steel mine frames, K21 or K24 (the K refers to the U-shaped cross section, while the number indicates the weight of the beam in kg per metre), and UNION lagging.

Jacking shafts have to be larger to accommodate the jacking frames and equipment. These will often be around 2.5 × 5.5m (depending on the equipment deployed). The ground support for such a shaft consists typically of frames of I-beams (usually IPE 240 or IPE 260). The individual frames are suspended by hangers on the initial frame that proceed the excavated section by about 1m into the ground ahead.

The mine frames are suspended on steel flat bars, 60 × 8mm through the yoke joints. I-beams could be suspended on varied types of hangers, e.g. the square/circular hollow beams welded on the axis of the I-beams or threaded rods passed through the web of the I-beams and fixed with hex nuts from each side or struts from outside with steel pipes forming the distance of the frames.

The author's company uses steel flat bars welded on both flanges of the I-beams as a cheap and easy solution.

Frame spacing starts at 1.3m and decreases with the depth according to the structural design. The distance should not reduce to less than 0.7m otherwise the steel sheets driven through frames would lead to a huge over excavation. In stable ground conditions the steel sheets are installed and wedged after the shaft excavation is advanced. In unstable conditions the sheets have to be forepoled around the frames to provide advanced support. Once shaft excavation is complete, a sump pit is constructed and 100mm of C8/10 blinding concrete is placed.

Prior to breaking through the lining of the shaft, the supporting frames within the breaking out area have to be removed and vertical girders installed on both sides of the opening to carry the load.

If the vertical girders of the shaft are supported by an I-beam the U-beams welded on the frames are used (usually UPE 120 – UPE 260 based on the depth and size of the future tunnel; sometimes the girder has to be anchored). If K21 or K24 steel mine frames are used to support the shaft, vertical girders are fixed to the frames by yoke joints. Sometimes the frame above the breaking out area has to be increased in size to accommodate the loads.

When excavating of shafts to a depth of 11m, a clamshell bucket excavator is used, with typical working progress of 0.50m to 0.75m per shift. Shafts that stretch deeper than this are usually excavated by bobcat and mucked out into skips by mining or gantry cranes, and rates of 0.35-0.60m per shift are common.

*Opposite, top:* ***Cross-section of tunnel in highly weathered rock on the right and in noncohesive soil on the left: (1) Steel Mine Frame – K24, (2) Forepoled Lagging – Steel Sheets UNION, (3) Longitudinal Braces – Steel Flat Bars 60 ´ 8, (4) Steel Strut with Stoppers – UPE 160 with welded stoppers from Steel Flat Bars 60 ´ 8, (5) Yoke Joint, (6) Face Lagging – Steel Sheets UNION welded through Flat Bars 60 ´ 8, (7) Face Timbering – Beech 40mm thick propped***

*Left:* ***Face timbering within highly weathered rock (Interceptor Sewer 'H' in Prague)***

## HAND TUNNELLING USING STEEL MINE SUPPORT FRAMES

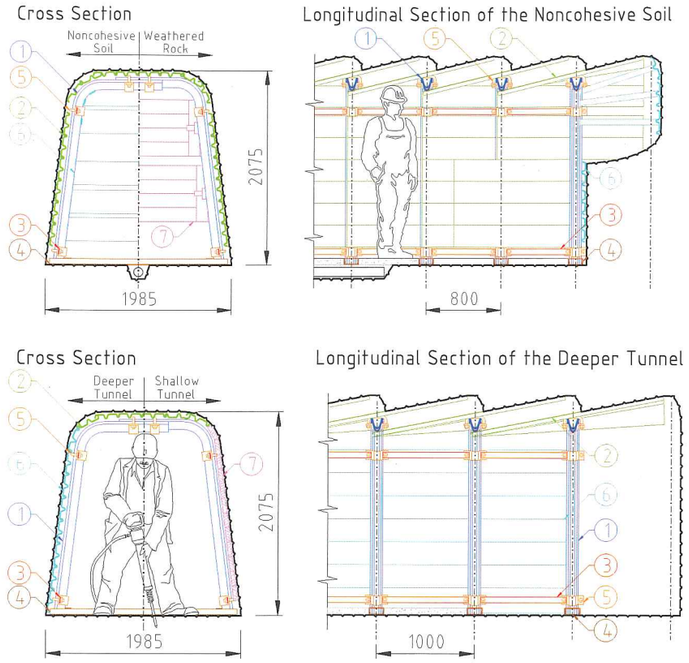
For trapezoidal tunnels, K21 or K24 steel mine frame support and UNION lagging is typically used. The typical cross-section area of these trapezoidal tunnels is from 3 to 4m². The crown lagging always has to be forepoled for safety reasons (to ensure the crown is supported at all times).

Tunnel walls can be simply lagged after the field is fully excavated in stable ground conditions. One frame is assembled per advance. The typical round length of 1m can be reduced to 0.6m if necessary (round length reduction leads to a greater over-excavation due to the greater angle of the forepoled steel sheets).

The steel frames are placed into steel struts, usually from UPE 160, with stoppers supporting the frames against closing under the horizontal pressure.

The tunnelling procedure is as follows:

1. Vertical girders are installed, the lining of the shaft within the break out area is removed and the first frame around the shaft lining is assembled.
2. The first set of forepoled steel sheets need to lean on a frame so the temporary frame has to be assembled roughly 0.8m in front of the removed lining. This frame can be dismantled after the first three frames are completed. In stable ground conditions where forepoling of the tunnel walls is not likely to be needed, a horizontal beam in front of the crown can be used instead of the temporary frame.
3. After forepoling is completed the excavation is advanced and the first frame erected. Sometimes the steel sheets cannot be driven ahead, and so have to be pushed concurrently with crown excavation.
4. As soon as the excavation of the full advance length is completed, a new steel frame is assembled, wedged and fixed to the previous one by four longitudinal braces fixed by yoke joints on the steel mine frames. If non-cohesive soil within the face is encountered, face timbering has to be kept in place.
5. New forepoling is installed through the last frame and the tunnelling cycle can be repeated.
6. As soon as approximately 8m of tunnel are completed, drainage is placed under the struts. Then the struts are backfilled with gravel and the electrical cables with lights plus ventilation duct are extended.




*Above:* ***Cross-section for medium weathered rock or cohesive soil intended to shallow tunnel (depth up to ca. 15m) on the right and deeper tunnels (depth over ca. 15m) on the left: (1) Steel Mine Frame – K21, (2) Forepoled Lagging – Steel Sheets UNION, (3) Longitudinal Braces – Steel Flat Bars 60 ´ 8, (4) Steel Strut with Stoppers – UPE 160 with welded stoppers from Steel Flat Bars 60 ´ 8, (5) Yoke Joint, (6) Lagging – Steel Sheets UNION, 7) Timbering – Beech 40mm Thick***

The available shapes and sizes of the frames were rigorously prescribed in the past. Nowadays, steelmakers are able to deliver any shape based on the designer's requirements. Thus the tunnel cross-section can be optimised for its specific purpose.

The tunnel cross-section used by the author's company for sewer pipes DN800 is shown in the figures. It is the optimum size for hand excavating tunnels of around 100m in length; not too large from an economic point of view and not too small in terms of feasibility. The original trapezoidal frames consisted of three pieces – equal hooks with one horizontal bracket on top. An optimisation is possible here: two pieces of frames only, directly bended together. It saves two yokes and bolts per frame.

Trapezoidal frames are most commonly used to support smaller tunnels. If a larger tunnel needs to be built, a rectangular box section with arched ceiling, elliptical or horseshoe frames is preferred.

## HAND TUNNELLING USING FRAMES OF STEEL FLAT BARS

This methodology uses the supported frames and steel/wooden lagging as the initial lining similar to the above-mentioned tunnel. However in this case the frames comprise steel flat bars (120 × 20mm) and the tunnel cross-section has to be oval (usually from 2 to 3m²). This lining is less stiff, therefore the lagging is more often made from wood (beech timber, 40mm thick), and the frames are sometimes even placed on wooden sills (180 × 100mm). Four longitudinal braces (steel flat bars 60 × 8mm) are bolted or welded to the frames. The round length is usually 1m with one frame per advance. Since the frames are flat, the forepoling causes only a slight over-excavation.

The shapes of these frames were limited in the past, but now any configuration can be manufactured. A recent innovation is the use of a frame made as a single hoop. This is carried into the tunnel horizontally, and then erected into its final support position. Compared to traditional methods, which used frames subdivided into three pieces (crown and two shoulders) that were bolted together, the new solution saves time and cost.

In both hand-tunnelling methods described above, the tunnels are excavated by pneumatic jackhammers and mucked out in hand carts moving along the guide strips made from UNION lagging. The usual advance rate of the trapezoidal tunnels is about 0.8m per shift while the 'Prague Frames' achieve roughly 1m per shift.

## MAN SHIELD PIPE JACKING

Man shield pipe jacking uses a totally different methodology. The lining is a plain steel jacking pipe with a diameter from 0.8m to approximately 2m (hand excavation of pipes smaller than 0.8m is prohibited in the Czech Republic). The jacking pipe consists of 2- to 3m-long sections (depending on the jacking rig and the shaft size), with the thickness of the skin ranging from 8 to 15mm (depending on the diameter and total length). A pipe section is placed on the jacking frame, welded to the previously jacked section, and then jacked into the ground. Pipe jacking consists of the following steps:

1. The space behind the lining in the back wall of the shaft is concreted. In front of this wall a thrust block is installed perpendicular to the tunnel axis. It has to be sufficiently strong to withstand the jacking forces and often consists of a grillage of welded I-beams or a cast concrete abutment wall.
2. The jacking frame is accurately fixed on the bottom of the shaft and positioned to the proposed tunnel

alignment;
3. The hydraulic jack is attached to the rear of the frame and connected with the power pack;
4. A front steel thrust block is then installed in front of the hydraulic jack to transfer the jacking force from the jack to the jacking pipe;
5. The jacking pipe is lowered onto the jacking frame and jacked into the ground to a predefined length;
6. Jacking stops and the muck is removed from the pipe to the shaft by hand carts, then lifted to the surface by crane; as soon as the jack has extended for full stroke, the jack is withdrawn and a spacer inserted between the hydraulic jack and the front thrust block;
7. As soon as the entire jacking pipe is in the ground, a new steel pipe section is lowered onto the frame, properly directed to the proposed alignment and welded to the previous one by welding.
8. If the tunnel is below the water table, a pump needs to be installed near the face; throughout the excavation, the quality of the air has to be measured (to keep the minimum 20 per cent of the oxygen, the air hoses of the pneumatic jack hammers are usually sufficient); the drainage hose, air hose, electric cable and lights are hung on the steel hooks welded on the wall of the jacking-pipe.

There is difference between man shield pipe jacking in soil and rock. While the soil is penetrated by the jacking pipe first and then the material within the pipe is mucked out (if the soil is unstable, face timbering must be installed), rock cannot be penetrated by the jacking pipe and must be hand excavated first using a pneumatic jack hammer, mucked out and the lining is driven afterwards.

The author's company typically uses two systems: a single jack system described above with the maximum jacking force of 1,800kN and a double jack system with maximum jacking force of 1,250kN.

Since the single jack system has higher capacity, it is preferable for longer drives (above 50m). Another advantage of this system is small power pack, which can be placed within the jacking shaft.

The advantage of the double jack system lies in the jack configuration. They are placed on the sides of the pipe and allow access into the tunnel at all times. This system is preferable for use in unstable ground where the pipe is jacked when each handcart is mucked out.

*Above: Initial lining of the trapezoidal steel mine support frames in stable ground - lagged/ timbered tunnel walls (Interceptor Sewer 'H' in Prague)*

It is important to pay attention to the jacking pipe preparation, especially to the following points:

- The pipe should be made by longitudinal welding (spiral welded pipes could adversely distort under the jacking force);
- The material of the pipe must be easy to weld (cast iron is not suitable);
- The accuracy of the joints of the individual pipes is highly important (even a small inaccuracy of the joint can cause difficulty in keeping the desired direction); the steel pipes can be cut to the desired length on site by oxyacetylene torch, but in this case they have to be welded back to the same position where they were prior to cutting (it is achieved by physically marking a point at the edge of the pipe);







- The assessment of the thickness of the jacking pipe should be made taking in to account the maximum jacking force and the potential eccentricity;
- A cutting edge has to be made at the leading edge of the first pipe to reinforce the edge and to create a thin annulus behind the jacking pipe to reduce the skin friction – the cutting edge is created as follows: a 200mm slight circle is cut from the jacking pipe, an longitudinal cut is made on the circle and this ring is dragged over 150mm of the leading edge of the jacking pipe (150mm lap joint, 50mm overlap of the cutting edge), the material missing by enlarging diameter from jacking pipe to cutting edge is added and everything is properly welded.

The workflow is highly dependent on the distance between the shaft and the face due to the confined conditions. In the first few metres of the excavation it is about 1.5 – 2m per shift and it gradually decreases to around 0.5m per shift. The ordinary inaccuracy of the tunnel drive is about 20mm per 10m. Therefore, for instance, if a pipe of OD 800mm should be installed for the length of 40m, a jacking pipe of ID 1,000mm is used. If the length of the drive is 60m, a jacking pipe of ID 1,200mm is preferred to take account of any error.

If higher accuracy is required, the jacking pipe can be steered to the required alignment. In rock it is done by over-excavating one side and propping the jacking pipe to the other. For incohesive soil conditions, a metal wedge made into a U-shape profile is used.

About 300mm of UPE240 is cut, and flanges are shaped to form a wedge with hooks at the top. The wedge is hung behind the cutting edge to increase the friction on one side of the jacking pipe.

As soon as the alignment is corrected, the hooks of the steel wedge are cut and the steering stops.

## STRUCTURAL DESIGN

The design, according to the Eurocode 7 approach 2, is used (combination A1 + M1 + R2). This approach applies safety factors to loads or load effects ($\gamma_G$ = 1.35 of the permanent loads and $\gamma_Q$ = 1.50 of the variable loads) and to the bearing capacity of the ground ($\gamma_M$ = 1.00).

The load acting on the tunnels can be derived from Terzaghi's Arching Theory or using modern FEM software with stress relaxation from 20 to 45 per cent. Both methods serve very similar results.

For determining the lateral earth pressure acting on the shaft, some designers prefer to use a conservative at rest pressure; others recommend applying a pressure equivalent to 2/3 of active earth pressure and 1/3 of at rest pressure, or reversely 1/3 of active earth pressure and 2/3 of at rest pressure.

For the lateral at rest earth pressure of the normally consolidated uncohesive soils determination, Jaky's formula can be used:

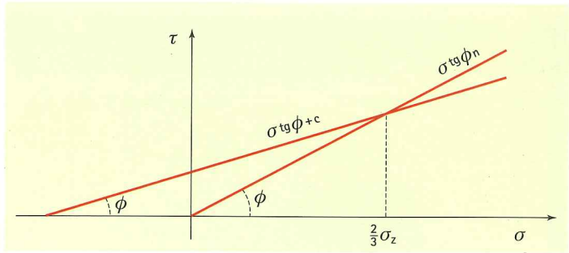
$$K_0 = 1 - \sin \phi$$

For cohesive soils a Jaky's formula with adjusted friction angle can be used:

$$\operatorname{tg} \phi_n = (2/3\ \sigma_z \times \operatorname{tg} \phi_{ef} + c_{ef}) / (2/3\ \sigma_z)$$

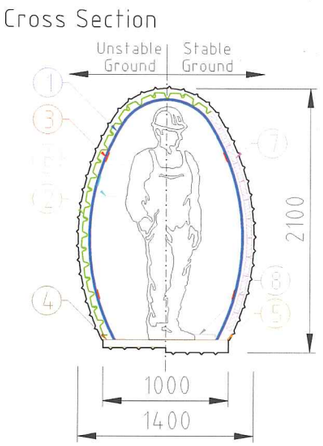
The '$K_0$' of the rock is often derived from the Theory of Elasticity:

$$K_0 = \nu / (1 - \nu)$$




*Above: The adjusted friction angle tg $\phi_n$ derivation (Peter Tureček - Zakládání staveb; Bratislava: Jaga, 2005)*

*Right: Two Options of Tunnel Cross-section (Stable Ground Conditions on the Right and Unstable on the Left): (1) 'Prague's Frame' - Steel Flat Bar 120 ´ 20mm, (2) Forepoled Lagging - Steel Sheets UNION, (3) Longitudinal Braces - Steel Flat Bars 60 ´ 8, (4) Steel Strut with Stoppers - UPE 140 with welded stoppers from Steel Flat Bars 60 ´ 8, (5) Sill 180 ´ 100mm, (6) Face Lagging - Steel Sheets UNION welded through Flat Bars 60 ´ 8, (7) Timbering - Beech 40mm thick, (8) Stopper - Timber 120 ´ 40mm Nailed to the Sill*




This formula can result in values that are too low; therefore the empirical values from 0.4 to 0.5 are sometimes preferred.

The lining is permeable so the water table pressure is not applied on the initial lining.

The derived load is put into the beam-spring model. The bedding stiffness coefficient 'k' of the radial springs can be derived from the empirical formula:

$$K = E / R$$
$$k = E / (1/2\ B)$$

For arches and lines, respectively, or using for instance Shchmitt formula:

$$k = 2{,}1\ E_{oed}^{4/3} / E\ I^{1/3}$$
$$E_{oed} = E_{def} / \beta$$
$$\beta = 1 - (2\ \nu^2) / (1 - \nu)$$

The springs can act at pressure only, thus a non-linear compression-only springs and nonlinear load combination has to be defined.

The analyses of the circular lining under uniformly distributed load would be unsafe since only a normal force would act on the beams; hence a varying distributed load taking into account the imperfection, varying surcharge load and non-homogenous ground conditions is

preferred.

According to DIN V 4034-1 the load should be redistributed into two perpendicular sections of 75 per cent and 125 per cent of the originally evaluated lateral pressure.

The design checks covering both normal force and the bending moment of the supporting frames are carried out using an interaction diagram. Furthermore, resistance of the lagging to the bearing bending moment has also to be checked.

*Above: View of the shaft-tunnel interface on the interceptor sewer in Benesov*

## THE PROS AND CONS OF THE METHODOLOGIES DISCUSSED

Generally, the basic advantages of the steel support methods versus shotcrete are:

- Low dust (very important especially within the small profiles);
- Immediate full-bearing capacity;
- Fast progress of construction;
- Consistent quality;
- Performance is independent of the climatic conditions;
- Gives the ability for a quick response to any unexpected situations;
- Low cost - especially for the temporary shafts as steel support can be dismantled and reused.

The main disadvantages of steel support are:

- It is always water permeable (except when used in pipe jacking applications). If a watertight lining is required by the project, a thin layer of shotcrete also has to be applied on to the lagging;
- It is only ever a temporary, initial lining, with the final lining usually made from watertight cast-in-place concrete, shotcrete or a clay/GFR pipe – based on the end use requirements of the tunnel;
- It has size limitations and is only convenient for tunnels up to about 25m² or shafts of up to about 40m².

Comparing the above-mentioned technologies, hand tunnelling with steel mine frames as support is the most universally applicable method, suitable for any ground conditions and any shape of cross-section.

Another advantage of a steel mine profile lies in the yoke joints – it is very quick, simple and safe (if the ground pressure grows too high, the beams slip within the joints and the excessive pressure is dissipated while maintaining the support function of the frames).

The bearing capacity of the steel flat bars is lower than the bearing capacity of the mine frames thus the maximum size of the 'Prague Frames' cross-section is limited. However the price is lower and the workflow is higher. Hence they are very convenient especially for small shallow tunnels in suitable ground conditions.

The main advantage of the man shield pipe jacking lies in the low cost, due to the small size of the excavated area (in the region of 0.5 to 2m²) and high safety both in the tunnel and on the surface, since the planar support and the optimum shaped circular cross-section are in place (the crew works within the sleeve of steel; usually there are only negligible settlements at the surface).

Therefore, this technology is perfect for tunnelling close to metro lines, under rivers or under railways with low overburden. It is convenient for arch canopy tube construction. Disadvantages of this method lie in the limitation of the feasible size and length of the tunnel.

Drives in excess of about 70m are feasible only with jacking pipe lubrication.

When comparing pipe jacking to modern microtunnelling, advantages include its universal use (one piece of equipment for any diameter; and feasibility even in extremely inhomogenous geology), simplicity (highly skilled operators are not needed), smaller site area (separation unit, operator cabin, large pumps, generator or power cabin are not used), lower purchase cost (only about five per cent of the price of the micro TBM) and low maintenance.

Disadvantages of the pipe jacking methodology compared to the micro TBM approach are: the maximal length of the drives being about three times shorter, workflow is approximately 10 times slower, and the working environment is less comfortable for the crew.

## CONCLUSION

There are a wide range of tunnelling methodologies available, some of them are more generally applicable to many situations, while others more specific and specialised.

No technique can be useful for every conceivable tunnelling situation.

Civil engineers need to be as familiar as possible with the wide range of tunnelling techniques available so they can design a solution using the most appropriate method for a particular situation

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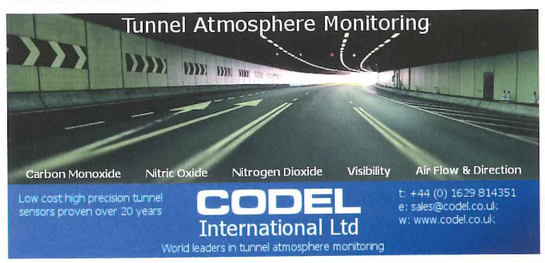


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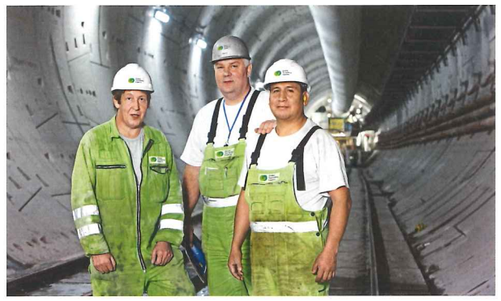

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# What's on

## 2016

### *International Symposium on Tunnel Safety and Security*
16-18 March 2016
Montreal, Canada
Tunnel safety and security is a challenge for both private and public sectors. ISTSS provides a forum to discuss current practice and emerging trends and research in safety and security.
*www.istss.se/en*

### *China Tunnel and Bridge Summit*
17-18 March 2016
Zhuhai, China
With the 12th five-year plan, China accelerated infrastructure construction and achieved a leap forward in development. Lots of sea- and river-crossing projects sprung up.
*www.merisis-asia.com*

### *NASTT's No Dig Show*
20-24 March 2016
Dallas, USA
The overall No-Dig Show program is focused on one objective: helping you maximise your investment in trenchless technologies, services and applications. If you sell trenchless products and services you'll want to be sure to exhibit.
*www.nodigshow.com*

### *Bauma Munich*
11-17 April 2016
Munich, Germany
The 31st meeting of the world's largest trade fair for construction machinery, building material machines, mining machines, construction vehicles and construction equipment returns to its traditional home: the Neue Messe Munchen exhibition centre in eastern Munich. Bauma is a global driving force behind innovations.
*www.bauma.de/en*

### *Infrarail*
12-14 April 2016
London, UK
The UK's definitive railway infrastrcture exhibit. Infrarail 2016 takes place against a background of high levels of investment in Britain's main line and urban rail infrastructure. Network Rail has embarked on its GBP 38 billion CP5 spending round.
*www.infrarail.com*

### *International Symposium on Submerged Floating Tunnels and Underwater Structures*
20-22 April 2016
Chongqing, China
This event, organised by the National Engineering Laboratory for Highway Tunnel Construction Technology, the China Institute of Mechanics, the Chinese Academy of Sciences, and the University of Naples will cover all topics from conceptual design up to operational emergency rescue.
*www.cmct.cn*

### *World Tunnel Congress and NAT*
22-28 April 2016
San Francisco, California
The 2016 World Tunnel Congress (WTC) and the 39th General Assembly of the International Tunnelling and Underground Space Association (ITA) will be held in conjunction with the UCA's North American Tunnelling conference.
*www.wtc2016.us*

### *Underground Construction Prague and EETC*
23-25 May 2016
Prague, Czech Republic
Delegates are cordially invited to the thirteenth Underground Construction (UC) Prague Conference.
*www.ucprague.com*

### *Swiss Tunnel Congress 2016*
15-17 June 2016
Lucerne, Switzerland
The annual Swiss Tunnel Congress (STS) is organised by the Swiss Tunnelling Society and is the premier event for tunnelling in Switzerland. Approximately 800 delegates attend from around 15 nations to take in the high quality presentations.
*www.swisstunnel.ch/en*

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

### *No Dig Live UK*
20-22 September 2016
Peterborough, UK
Following the success of No Dig Live UK held in September 2014, the 13th biennial trenchless technology exhibition, outdoor demonstrations and seminars will return to Peterborough. Visitors to thie show were offered a wide ranging programme of educational opportunities.
*www.nodiglive.co.uk*

### *Innotrans*
20-23 September 2016
Berlin, Germany
InnoTrans is the leading international trade fair for transportation technology, and takes places every two years in Berlin, Germany. The event is sub-divided into the five segments Railway Technology, Railway Infrastructure, Public Transport, Interiors and Tunnel Construction.
*www.innotrans.com*

### *BTS Conference and Exhibition*
11-12 October 2016
London, UK
The British Tunnelling Society is pleased to announce the highlight of its 2016 events calendar, held at the QE2 Conference Centre in Westminster. Presentation synopses of 250 words are now being accepted for consideration with a deadline of 26 February. For more details please visit the society website.
*www.britishtunnelling.org.uk*

### *Expo Tunnel*
19-21 October 2016
Bologna, Italy
ExpoTunnel is an exhibition dedicated to the world of tunnelling, drilling, mining, underground construction and research. It is an opportunity to meet in a global framework of supply and demand of high technology and its field applications, with the chance to learn new methods and harness new techniques.
*www.expotunnel.it*

### *Bauma China*
22-25 November 2016
Shanghai, China
Bauma China is Asia's largest and most important event for the construction industry. It attracts international buyers—a fact that guarantees a high return on your investment as well as sustainable success. The show is a platform for product presentations and a grand industry party for communication.
*www.bauma-china.com*







### *TBM DiGs*
16-18 November 2016
Istanbul, Turkey
Turkey has a great potential of Tunnelling and in the near future the country is expecting to see upwards of USD 35bn of investment in underground construction.
*www.tbmdigsturkey.org*

### *Bauma Conexpo India*
12-15 December 2016
Delhi, India
The International Trade Fair for Construction Machinery, Building Material Machines, Mining Machines and Construction Vehicles—provides the construction industry in India with a professional platform for networking, investment and the exchange of ideas and information. The show launched in 2011 and did an impressive job of putting this quality standard to the test.
*www.bc-india.com*

## 2017

### *World Tunnel Congress*
9-16 June 2017
Bergen, Norway
The theme of the 2017 WTC is 'surface problems - underground solutions'. The Norwegian tunnelling industry produces tens of kilometres of drill and blast tunnel every year and is keen to share its expertise with attendees.
*www.wtc2017.no*

### *GeoMEast2017*
15-19 July 2017
Sharm El-Sheik, Egypt
Recent rapid construction in Egypt has provided great opportunities for tunnel engineers to use their knowledge and talents to solve many challenging problems with innovative solutions and cutting-edge technologies. GeoMEast 2017 will provide a showcase for recent developments.
*www.geomeast2017.org*

## 2018

### *World Tunnel Congress*
20-26 April 2018
Dubai, UAE
The World Tunnel Congress heads to the United Arab Emirastes in 2018, and demonstrates the rise of the Middle East to the centre stage of the global tunnelling market.
*www.uaesocietyofengineers.com*

## *The British Tunnelling Society*

The BTS has a membership of over 814 individual and 266 corporate members. It is one of the most vibrant gatherings of professional tunnellers in the world and traces its history back to its founding in 1971. Regular BTS monthly meetings are hosted at the Institution of Civil Engineers in London from 5.30pm every third Thursday of the month. In recent years, the BTS Young Members (BTSYM) group has also begun hosting its own events.

### *The history of the Davy Lamp (joint BTS-MinSouth event)*
18 February 2016
The presentation will be about the History of The Davy Lamp and will be given by a mine rescue professional who was involved with the Chile Mine Rescue. It should prove to be of great interest to both mining and tunnelling professionals.
**Speaker: Brian Robinson of Mine Rescue**

### *Mission Control: monitoring temporary works in tunnels*
17 March 2016
The presentation will describe the application of 'cloud based data' to real time review of temporary works performance against design within tunnels, illustrated by a number of example projects in the UK and Hong Kong.
**Speaker: Angus Maxwell of Maxwell Geosystems Ltd, Anmol Bedi of BAM Nutall**

### *Harding Prize Presentations*
21 April 2016
The annual competition is named in honour of Sir Harold Harding, founder chairman of the BTS and is open to engineers aged 33 or under. Entrants must submit an original paper relating to any aspect of tunnelling which they consider of interest to the industry. The winning paper is selected by members of the BTS Committee. Further details can be found on the society website under 'The BTS' tab, 'Awards' section. The winner of the Harding Prize receives two tickets to the BTS Annual Dinner, a copy of Sir Harold's book 'Tunnelling History and My Own Involvement', and a cheque for GBP 500.
**Speakers: Harding Prize finalists**

### *BTS Annual Dinner*
6 May 2016
The BTS holds an Annual Dinner each year in May. The 28th Annual Dinner will be held at the Brewery on Friday 6 May 2016. Further details will be available shortly before booking opens in early February. Last year's event drew 848 attendees, the largest number since the BTS began keeping records in 1996.
**Tickets for this event will become available from the BTS website**

### *AGM followed by presentation on Singapore's Thomson Line*
19 May 2016
Singapore's 30km all-underground Thomson Line (TSL) involves the operation of 30 TBMs to complete the twin running tunnels and the construction of 22 underground stations including 6 interchange stations. This involves a number of challenges in complex urban areas and partially reclaimed land. The presentation will concentrate on TSL-A and TSL-D with project features such as varying geotechnical conditions, SFRC and RC segment design, design of bored tunnels in consolidating marine clay, under- and overcrossing of existing railway lines, tunnelling beneath operational stations, as well as three-way Interchange Stations.
**Speakers: Andreas Raedle, Leo Suhaendi and Rob Harding of Arup, and a yet to be confirmed representative of the LTA**

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

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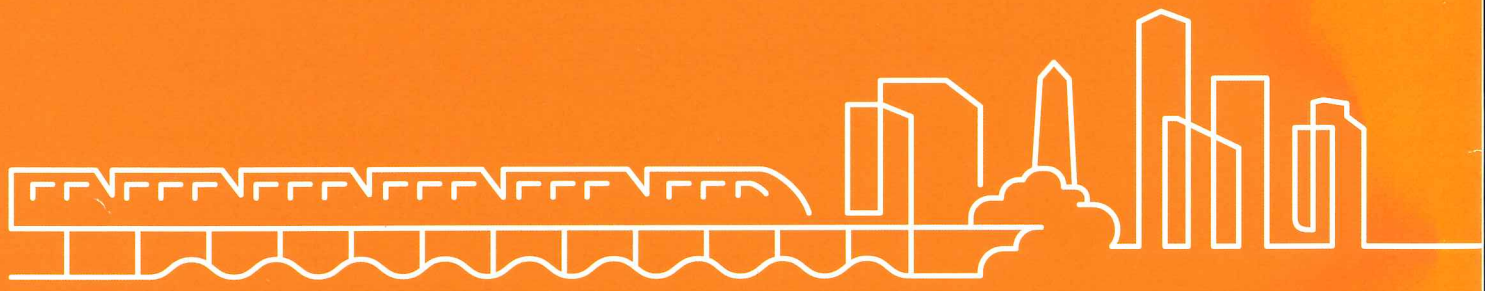

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