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ROCK ME AMADEUS

NATM is a frequently misunderstood approach to tunnelling. Its definition, its use and its advantages are often the subject of debate. In this issue of *Tunnels*, Austrian Society for Geomechanics (OeGG) president Wulf Schubert attempts to tackle the issue.

Fifty years of NATM were celebrated at the Geomechanics Colloquium in Salzburg last October as the OeGG welcomed the industry to its 61st event.

The International Society of Rock Mechanics was founded in Salzburg that May in 1962. And at that year's colloquium, Professor Rabcewicz coined the phrase 'New Austrian Tunnelling Method' (NATM).

It was the first visit to the show by the current *Tunnels* team, following recommendations, invitations and coercion by engineers from within Austria and abroad. And it didn't disappoint. Gone were the too often tepid offerings of the usual conference lecture sessions, as the first round of presentations brought together speakers from around the world to explore regional evolutions of NATM.

Mercifully, the planned use of underground space was only hinted at as a topic. The highlight was the opening session on regional NATM developments. As chair, Wulf Schubert mentions the 'occasional attacks' on the method that have not prevented its adoption around the world in some of the most difficult geological conditions.

To someone familiar with British tunnelling history, the Heathrow Collapse stands out, and is brought up in the British offering to the regional session by David Hindle and Maurice Gooderham. They state that as a result of the collapse, all NATM work in the UK was suspended, and an ICE commission decided that in soft ground it was not possible to use the NATM philosophy of mobilising inherent ground strength through deformation. Resulting HSE publications have had a damning effect on NATM in the UK to this day.



Cover
The largest TBM is full assembled and named Bertha prior to departure for the Alaskan Way project in Seattle

Next issue
Tunnels International looks to North America for updates on the latest projects from the new world. A new feature topic 'the tunnel environment' will look what makes a tunnel under construction a safe place to be. Precast segments will be the technical

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Alex Conacher
Features Editor



A challenge is laid down in the conference – for more engineers to come and present their country's ideas on NATM in front of a vocal audience. As for British attendance at the 2012 colloquium, the three-strong contingent (including *Tunnels*) is telling.

The comment written by Hindle (*Tunnels* International August p.46) previewed his and Gooderham's presentation, and asked 'what is SCL?' For although NATM is a sprayed concrete method, it has completely different implications to the British 'Sprayed Concrete Lining' design concept which attracts such amusement in Austria for its conservative approach. British engineers in particular are invited to present their views on the sequential approach in future colloquiums.

Perhaps the paper presented by Schubert (pp.39-42) will help with some of the confusion, as even the ITA president is told after his presentation that many of his examples are not truly NATM. Schubert tells *Tunnels* that his hope is to end the mysticism surrounding tunnelling and for it to be seen as a regular engineering task.

See you there this year

In this month...

10 YEARS AGO

The first Herrenknecht gripper TBM for the Gotthard base tunnel will be assembled on site next month ready for the start of tunnelling in May. The workshop assembly of the 9.58m diameter machine was completed last month.

20 YEARS AGO

Editor Peter Darling asks who will be hit hardest by the doldrums of global recession, contractors or consultants. The contractor is burdened with the cost of premises and plant. The consultant on the other hand, while benefiting from low overheads as an independent operator, also enjoys very little security. The larger firms struggle to keep their top engineers stimulated and 'watered'. Given the choice, both would probably agree to switch, but would probably prefer to be in the position of the client.

40 YEARS AGO

Felix Gaye gave a BTS presentation on the basic study of rock excavation by boring machine. He stresses that the progress of applied science in this field has been empirical – and therefore slow. Gaye addresses a theory of the efficiency of boring operation based on a constant cross-section of attack, highlighting that much more effort has been expended on improving cutters than improving approach.

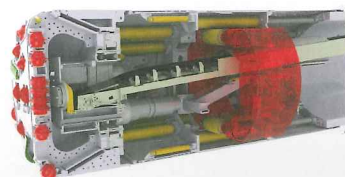
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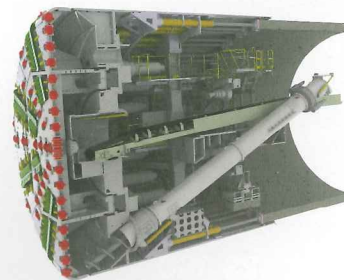
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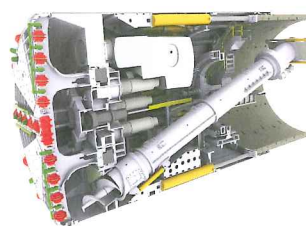
Double Shield Rock



Convertible (Dual Mode)



Earth Pressure Balance

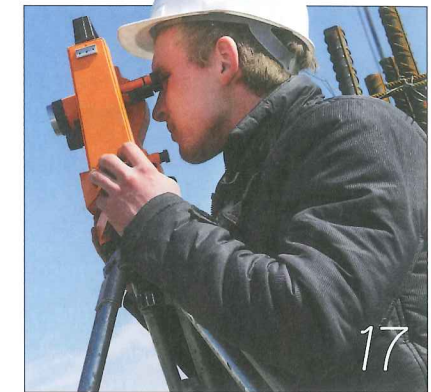
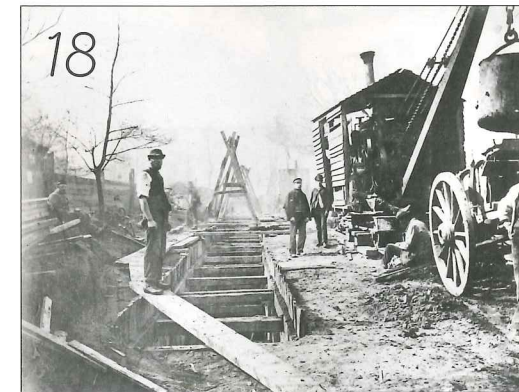
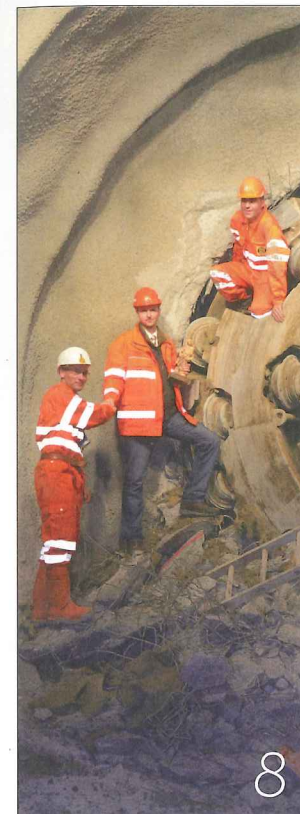


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Contributors

Diana Pfeff

Diana has been involved in the tunnelling business for seven years. Working in the R&D department of Herrenknecht she was responsible for the development of the Direct Pipe Technology in 2007. Since then she is product manager for this product. She studied civil engineering and environmental technology at the University of Stuttgart and started working for Herrenknecht right after she got her degree.



Wulf Schubert

Wulf is head of the Institute of Rock Mechanics and Tunnelling at Graz TU in Austria. Wulf served as vice president at large for the ISRM from 1999 to 2003, and has been president of the Austrian Society for Geomechanics since 2007. He previously worked for Geoconsult and continues consulting as a partner of Gruppe Geotechnik Graz Consulting Engineers.



TUNNEL SOLUTION PROPOSED TO TACKLE JAKARTA FLOOD PROBLEM

Indonesia The Jakarta administration announced that it is planning to build a deep-water tunnel to help the city cope with its seasonal flood problem. Jakarta governor Joko Widodo said that the tunnel will be built from Cawang in East Jakarta, along Jalan MT Haryono, up to Pluit in North Jakarta.

"This needs to be done because we have to race with the continuous development of residential areas and buildings. There should be balance," Joko said. "It is true that this is not in the blueprint, but we do not have to solely rely on that, there should also be a breakthrough.

"We have been inundated by floods for decades now."

He said that he had ordered all related city agencies and municipal leaders to conduct the necessary field checks for the project. He said that all institutions in the city should work together in developing the project.

"So far, there are only separate programs. The [Jakarta] Public Works [Agency] wants to do this in March, the state clean water company wants to

do that in June. Then there is also the telecommunication company, Telkom, which wants to do another thing in September. How can this happen? If everyone wants to work at the same time, then do the deep tunnel," he said.

According to Joko each institution so far was taking turns in digging up areas already dug up and filled again by others. The tunnel, he said, would be able to accommodate the needs of all those institutions.

Earlier, on 26 December 2012, Joko inspected the underground drainage network along Jalan Thamrin and found that the diameter of those drains was at 600mm and that, he said, was not enough to accommodate the high volume of rain.

"It is also impossible to put every utility network into a drain of 600mm. Rains in the old times were not as extreme as now and the volume of water could be absorbed but now everything is covered in concrete and therefore all waters are flowing into the drains," he said.

Jokowi said that he estimated that

the deep tunnel project is estimated to need some IDR 16tn (USD 1.66bn), which will come from the city budget and the private sector. He estimated that the project will take four to five years to complete.

The drainage system on Jalan Thamrin was constructed more than 40 years ago.

"This was made in 1970 and it was in accordance with the rain intensity at the time, which was not as high as it is today," said Jakarta Public Works Agency head Ery Basworo.

Basworo said that Jalan Thamrin didn't have many water absorbers that could accommodate rainfall of more than 100mm/s.

"The 600mm diameter [drain] could only accommodate medium-intensity rains of about 55mm/s, he said, adding that the tunnel should have a diameter of at least one meter.

Basworo added that he had proposed widening the tunnel diameter to 1m for a 2km stretch. He added that the widening of the tunnel will start from the Sudirman area.

Eight workers die in blast

China Eight construction workers were killed and five others injured in an explosion at the construction site of a railway tunnel in north China's Shanxi Province on 25 December 2012. The provincial government made the announcement, which was reported by local media.

Authorities stated that the accident happened when construction workers tried to re-blast a hole. Excavation work was in process on the central and southern portions of the Liangshan tunnel when explosives used for demolition went off, the authorities added.

The Nanlu-Liangshan tunnel in Linfen City is being built by Erchu, a subsidiary of China Railway Tunnel Group. According to reports, the project manager allegedly tried to conceal the accident.



The London Underground celebrated 150 years since the first service on 9 January 1863. The locomotive was steam powered and ran from Paddington to Farringdon. The UK's capital has kicked off a year of celebrations related to the event. Turn to the Big Picture story on pp.14-15 for more.

Largest TBM named

USA The world's largest-diameter tunnelling machine, which will begin boring the SR 99 tunnel beneath downtown Seattle next summer, now has a name, the Washington State

Department of Transportation (WSDOT) announced recently. Following a competition to name the machine, the winning entry was Bertha.

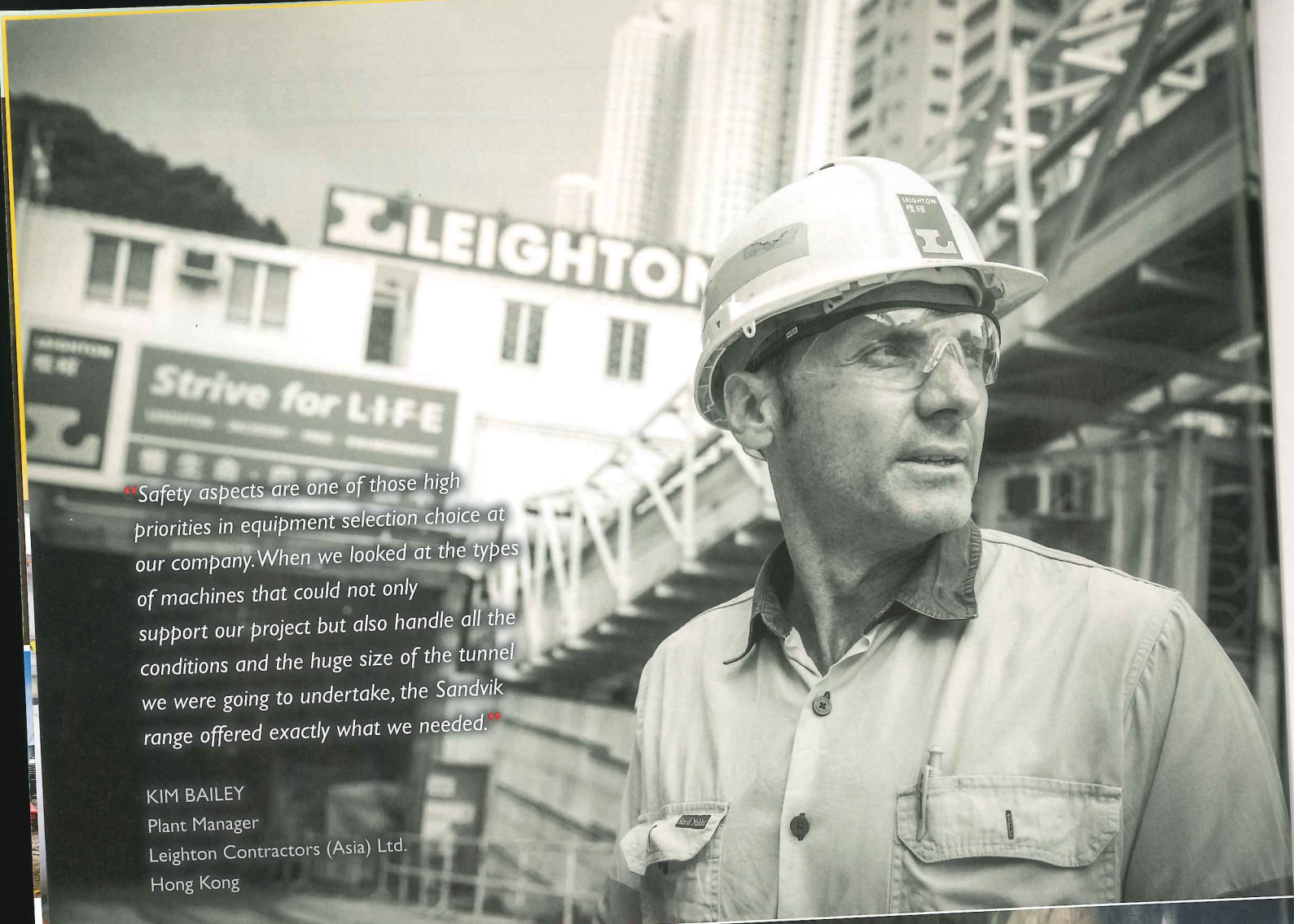
Bertha's name was chosen as part of a contest for kindergarten through 12th grade students. Names

had to be female and have significance to Washington state heritage, life, nature, transportation or engineering.

"This project is about breaking new ground," said Charley Royer, former mayor of Seattle and a contest judge. "Like the SR 99 tunnelling machine, Bertha Knight Landes was one of a kind. It's only fitting that the machine bears her name."

The winning name was submitted by two entrants: Darryl Elves' fifth-grade class at Poulsbo Elementary School and Elijah Beerbower, a second-grader at Lincoln Elementary School in Hoquiam. All of the winners will be invited to Bertha's dedication ceremony in Seattle next summer.

They will also receive special t-shirts and the honor of having the name they chose painted on the side of the machine.



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Plant Manager
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SWISS SAFETY TUNNEL MAKES FINAL BREAKTHROUGH

Switzerland The TBM for the Milchbuck Safety Tunnel in Zurich, Switzerland, has made its final breakthrough, a spokesman for Robbins announced last month. The TBM successfully excavated through 400m of compact rock and 600m of fractured zones with overbreak.

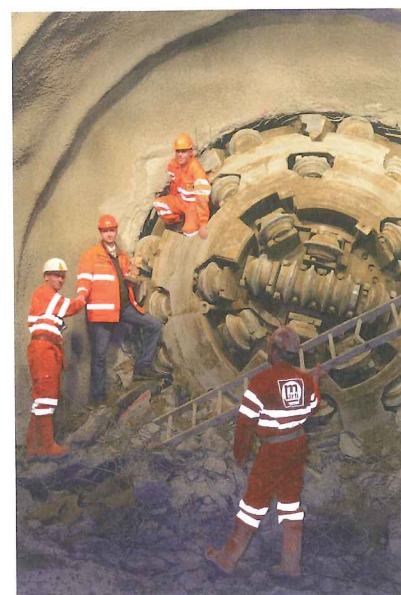
The tunnel required two methods of excavation due to a split in geology. Some 1,000m of TBM tunnel were bored through molasse rock, while a 400m conventionally dug section was located in unconsolidated rock. The Robbins Main Beam machine, for contractor Marti Tunnelbau, completed tunnelling in March and was stopped in order to allow the completion of the conventionally excavated tunnel.

"The performance went very well," said Thomas Guggi, Marti Tunnelbau.

"It was hard work, but we had a special back-up to apply 360 degree shotcrete in these sections. The design allowed for a 200mm thick, wet application using two shotcrete robots for the full length of the tunnel."

The TBM breakthrough marks the completion of the fourth tunnel for the 4.15m diameter Robbins machine, which underwent major refurbishment in 2002. "We are proud the TBM refurbishment was managed in such a short time, and without technical interruptions," added Guggi.

The safety gallery runs parallel to Zurich's Milchbuck Road Tunnel, a heavily used passage that needed to be updated to modern safety standards. The safety tunnel, for Swiss federal office ASTRA, includes five cross passages currently under construction.



Above: The final breakthrough came after a 400m excavation through compact rock and 600m of fractures

Tunnelling begins in southeast London

Great Britain Crossrail's fifth tunnelling machine, Sophia, began her journey from Plumstead to North Woolwich as part of the construction of a tunnel under the River Thames for London's new rail link, the developer announced last month. As the only slurry machine, the TBM is equipped to deal with the chalk, flints and the wet ground conditions that it will encounter in the southeast region of London.

The 110m-long TBM is scheduled to drill at an average rate of some 100m a week, installing precast concrete segments as rings to form the tunnel lining as it advances forwards.

When Crossrail opens, up to 12 trains per hour during peak time will link southeast London and the Royal Docks with Canary Wharf and central London.

Stephen Hammond, Crossrail minister, said: "The launch of Sophia, the fifth tunnelling machine on Crossrail, demonstrates

the great progress that the project is making".

Across the Crossrail project, eight tunnelling machines will construct 21km of twin tunnels under London. The Crossrail route will pass through 37 stations and run 118km.

Contract awarded for Hong Kong MTR line

Hong Kong Hong Kong's MTR Corporation has awarded a USD 440M tunnelling contract on the new Shatin to Central Link (SCL) railway to Gammon Construction, which is 50 per cent owned by Balfour Beatty. The company will work alongside Kaden Construction on the project.

The contract includes the construction of two cut and cover tunnels covering with a total track length of 1km. It will connect the existing East Rail Line to the Hung Hom Station and the Hung Hom Station to the future Ho Man Tin Station. Work is expected to be completed in 2018.

"This is another significant contract award by the Hong

Kong MTR Corporation," said Ian Tyler, chief executive, Balfour Beatty. "Not only is it a testament to the strength of the relationship with this customer, but also demonstrates the value that our partners put on the experience and expertise we have in delivering major transport projects around the world. One of our key strategic sectors is transportation and this activity in Hong Kong builds on our strengthening global experience in rail."

The 17km-long SCL project includes 10 stations, of which six will provide interchanges to existing lines. It will provide a much needed railway service to the East Kowloon district. Total use is predicted at 1.1 million passengers daily in 2021.

Wall panels removed in Boston tunnel

USA Some 26 loose panels were removed from inside the Sumner Tunnel in Boston, US, in late December following an inspection, local media reported.

Massachusetts Department of Transportation (MassDOT) is ordering replacement materials for the tunnel, with repairs to come in weeks.

Each enamel-coated metal panel measures 1.2 by 2.7m and weighs approximately 100lbs (45kg). About three dozen workers performed pull tests on all 2,400 panels and found 26 were loose because the stainless-steel bolted connections holding them in place had corroded, a MassDOT spokesman said.

The inspection of the Sumner tunnel was triggered by findings inside the Callahan tunnel, which runs parallel to it. The Callahan was shut down on 21 December, 2012 after a single panel fell. There are 2,800 panels in the Callahan. No commuters were injured in that incident.

The weakened bolting systems in the Sumner were not found in clusters but throughout the tunnel. More advanced deterioration was seen in the Callahan, with rusting extending to the framework that holds the panels in place.

News briefs

USA

Two TBMs broke through on twin tunnels for the Toronto-York Spadina Subway Extension (TYSSE) on 29 November 2012. While normally, one TBM lags behind the other to reduce the risk of settlement, at the very end of this drive both machines made good progress and arrived a few days apart, making it possible to break both machines through at the same time. The TBMs launched in December 2011 and February 2012, respectively. The diameter of each machine is 6m and the tunnels will have a 5.4m completed diameter.

GREAT BRITAIN

An undergraduate Costain engineer at the University of Exeter, has won a regional structural engineering award for his research into using optical fibre sensing to monitor strain within sprayed concrete. Ben Ford researched and tested how optical fibre cables could be used to measure performance within structures.

MASSIVE TBMS ORDERED FOR SICILY ROAD TUNNEL

Sicily French TBM manufacturer NFM Technologies has been awarded two new contracts including one for the largest TBM ever built in France, the company announced last month.

This machine, with a diameter of 15.08m, will be built for the planned Caltanissetta road tunnel in Sicily on behalf of the Italian company, CMC Cooperativa Muratori Cementisti Ravenna, and its partner, Tecnis. The new motorway connects Porto Empedocle to the Caltanissetta junction and aims to improve road connections to south Sicily by expanding the currently operational regional road network.

The order includes the design,

manufacture and on-site assembly of the TBM, which is expected to weigh some 3,200t and will be more than 100m long. The TBM is expected to be delivered to site this autumn. It will then be used to excavate two tunnels, each with a length of 3,900m.

NFM Technologies has also recently added the supply of another TBM for Astaldi to its list of orders. This EPBM will be used to excavate the extension to the Bucharest metro system. The machine, with a diameter of 6.6m, will dig out four tubes with a length of 500m. The tunnels will be located to the northwest of the town, on line four, which includes the stations of Bazilescu park and Lake Straulesti.

Bangalore Metro Rail progresses

India TBM Helen was 50m away from the Vidhana Soudha Metro station, where she is expected to complete the journey within days as Tunnels went to press. The total length of the tunnel from Central College station up to Vidhana Soudha station is 724m, Helen has progressed up to some 670m.

The tunnel is part of the underground stretch of the Namma Metro East-West line. The second TBM, called Margarita, has progressed up

to 426m but rocky ground conditions have slowed the progress of its work.

Jeddah metro design 'almost complete'

Saudi Arabia Transport minister Jabara Al-Seraisy said the design work on the Jeddah metro project in Saudi Arabia is nearing completion.

"The design of a light train project in Jeddah will be completed five months from now. After that it will then be submitted to the higher authorities for their

consideration," Al-Seraisy said in December 2012.

"The study of metro trains in Jeddah is part of the ministry's mass transit system projects in Saudi cities," Al-Seraisy said.

According to an earlier statement made by the Jeddah Municipality, the proposed light rail transit system, resembling the Dubai Metro, will be 108km-long, running across the city. It will also consist of three major lines, which will be designated in different colors: orange, blue and green.

The planned mass transit system in Jeddah also includes a bus service using 816 buses to link metro stations with all the residential districts in the city. Buses will run 750km in various districts.

A municipal study showed that 96 per cent of Jeddah's inhabitants use cars as their primary mode of transportation and only 4 per cent of the population uses public transport.

Steps to introduce metro projects in Riyadh and Makkah are also under way. While the six routes of the Riyadh project will be 181km long, the Makkah metro is projected to be 182km with six branches.



Above: Bangalore's first TBM, Helen, was due to break through shortly after Tunnels went to press

KLANG VALLEY MRT. ON TRACK

Malaysia The first line of the Klang Valley mass rapid transit (MRT) system, the Sungai Buloh-Kajang Line, is expected to make solid progress in 2013, said Malaysia's Mass Rapid Transit Corp (MRT Corp) chief executive Datuk Azhar Abdul Hamid.

It was reported that about 3 per cent of construction works had been completed as of 18 December 2012.

"Land issues are mostly resolved. However, there are still a few more to be managed, and tunnelling should start toward the second quarter of 2013, as we expect tunnel boring machines to arrive in Malaysia in the

next quarter," said Hamid. "Ultimately, work is on track and the delivery date of MRT Line One remains at July 2017."

Line One, which connects Sungai Buloh to Kajang via a track that runs through the city centre, is made up of two phases.

The first phase is from Sungai Buloh to Semantan, while the second is from Kajang to Taman Maluri.

It is expected that the first phase would be operational by December 2016, and the second by June 2017.

MRT Corp has been awarding tenders for MRT Line One since the fourth quarter of 2011. To date, it has

awarded almost MYR 20bn (USD 6.6bn) worth of advance, civil and systems works. There are about 20 more tender packages to be awarded, and in total, the balance of the award should not exceed MYR 3bn (USD 1bn), bringing the construction cost of the MRT Line One to about MYR 23bn (USD 7.6bn).

MRT Corp has awarded a total of 54 packages worth MYR 20bn (USD 6.6bn) out of 85 packages.

At MYR 23bn (USD 7.6bn), the price tag for MRT Line One was still well within the budget set by the Government, partly supported by the reduction in land acquisition costs.



Above: February will see Niagara's support equipment removed

Niagara gears up for final chapter

Canada The Niagara Tunnel Project is expected to be completed this year with the flooding of the tunnel due in mid to late March, Ontario Power Generation (OPG), Strabag and Robbins revealed last month.

January will see the removal of remaining carriers and bridges from within the tunnel to the outlet channel where they are dismantled and lifted to the surface. Castonguay Blasting Company continues the blasting process to remove the rock plug separating the outlet channel from the hydro feeder canal. In February, the removal of all of the work related equipment support utilities including pipelines and

power lines is expected.

OPG awarded a CAD 600M (USD 607.7M) design-build contract for the Niagara Tunnel to Strabag on August 18, 2005, based on its proposal to excavate the tunnel with a 47.4ft (14.4m) Robbins Main Beam gripper TBM and a two-pass lining. The project will bring more water from the upper Niagara River to the Sir Adam Beck hydroelectricity generators. The additional water will allow OPG to generate enough electricity to power some 160,000 homes.

Abu Dhabi tunnel opens

UAE The project manager the 4.2km Sheikh Zayed Street project in Abu Dhabi, UAE, celebrated the project's completion with the public opening of the final section

of the project, the Zayed Street Tunnel, late last year.

Tom Topolski, Louis Berger senior VP and Middle East general manager, said: "The Zayed Street Tunnel marks one of the longest tunnels in the Middle East, and is a signature transportation achievement for the UAE. The tunnel will relieve surface traffic congestion along Sheikh Zayed Street—a major artery in downtown Abu Dhabi—by approximately 20 per cent."

As the program manager, Louis Berger has been responsible for scheduling, financial, contractual, quality assurance and coordination activities, including ongoing

strategic advice to the Municipality, the company stated. The Louis Berger team worked closely with contractors and other stakeholders to help mitigate the technical, social and economic challenges that occur when constructing an eight-lane tunnel in the downtown portion of a major metropolis with a population of more than 600,000 people.

British rail tunnel turns 175

Great Britain Members of the Institution of Mechanical Engineers gathered last month to mark the 175th anniversary of the completion of the Kilsby railway tunnel.

The Institution of Mechanical Engineers stated that the Kilsby Tunnel proved to be one of the biggest challenges in building the London and Birmingham Railway, due to the presence of unexpected quicksand.

A dinner in 1837 marked the completion of the tunnel. John Wood, past president of the Institution of Mechanical Engineers, said: "George and Robert Stephenson were the two first presidents of the Institution, and as Institution members we're hugely excited to be able to mark this anniversary at the very same location where this dinner took place in 1837."

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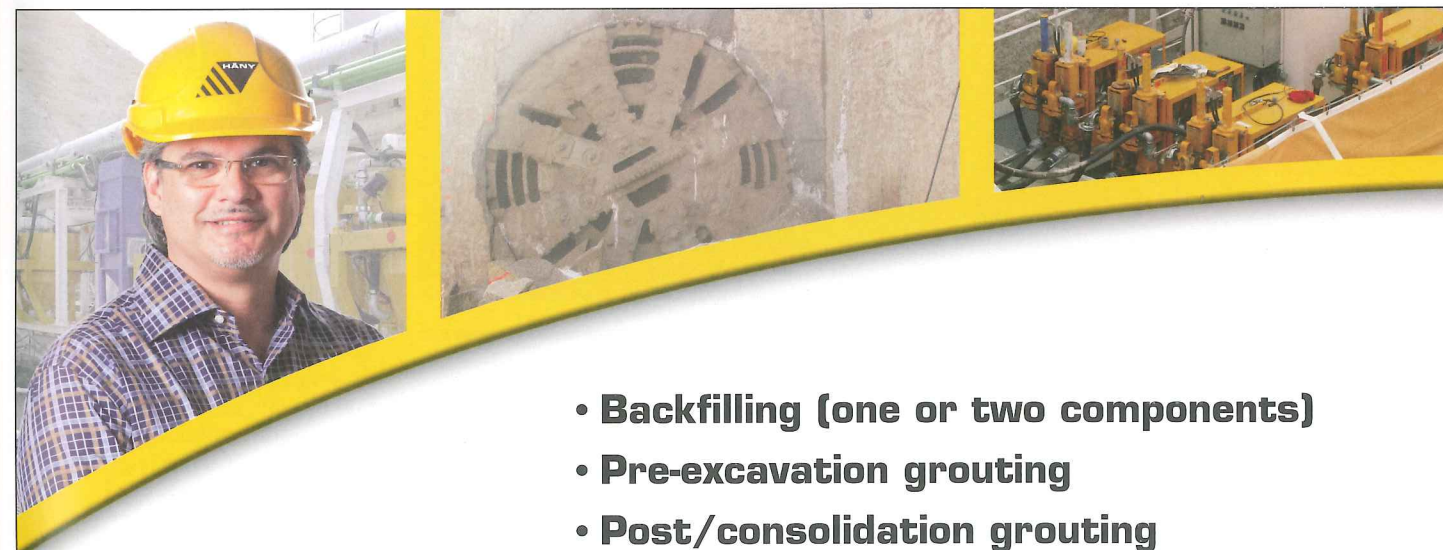


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ATLAS COPCO BUYS PART OF MEYCO

Sweden Swedish equipment giant Atlas Copco has agreed to acquire the Switzerland-based Meyco Equipment business from BASF Construction Chemicals Europe, it was announced late last year. Atlas Copco stated that the contract broadens its offering with mobile equipment for applying sprayed concrete in underground operations.

Operations will continue at the only production site of Meyco Equipment in Winterthur, Switzerland. Some 40 employees work at the site. Its products include carrier-mounted concrete spraying equipment, concrete spraying arms, pumps and dosing units. Sales are mainly for underground construction projects in Europe, Asia and the Middle

East. Both parties have agreed not to disclose financial details of the transaction.

"This acquisition is a good strategic fit for Atlas Copco as it broadens the offering for our existing customers," said Bob Fassl, business area president for Atlas Copco Mining and Rock Excavation Technique.

Share tracker

Company	December	January	Change (%)
Aecom (NYSE: ACM)	23.99	24.88	▲ 0.89 (3.7)
Atkins (LSE: ATK)	764.00	772.5	▲ 8.5 (1.1)
Balfour Beatty (LSE: BBY)	263.00	290	▲ 27 (10.3)
BASF Global (XETRA: BAS)	71.55	71	▼ 0.55 (0.8)
Bekaert (BSE: BEKB)	19.23	22.16	▲ 2.93 (15.2)
Bilfinger Berger (DUS: GBF)	76.40	72.78	▼ 3.62 (4.7)
Caterpillar (NYSE: CAT)	87.95	95.19	▲ 7.24 (8.2)
Costain Group (LSE: COST)	243.25	261.25	▲ 18 (7.4)
Ferrovial (MCE: FER)	11.24	12.06	▲ 0.82 (7.3)
Hindustan Construction Company (BOM: HCC)	17.9	18.9	▲ 1 (5.6)
Hochtief (XETRA: HOT)	42.58	46.22	▲ 3.64 (8.5)
Morgan Sindall (LSE: MGNS)	516.00	541	▲ 25 (4.8)
Sandvik (STO: SAND)	101.80	104.5	▲ 2.7 (2.7)
Shanghai Tunnel Engineering (SHA: 600820)	8.52	8.83	▲ 0.31 (3.6)
Strabag (LSE: STR)	21.70	19.88	▼ 1.82 (8.4)
URS Corporation (NYSE: URS)	39.55	40.63	▲ 1.08 (2.7)
Vinci (EPA: DG)	35.41	37.1	▲ 1.69 (4.8)

Prices are taken on 12th of each month. NYSE is in USD. LSE is in GBP. STO is in SEK. BSE, EPA, MCE, STR and XETRA are in EUR. BOM is in INR. SHA is in CNY.

Central bank rates

	Rate (%)
AUD	3.00
BRL	7.25
CAD	1.00
CHF	0.00
CNY	6.00
EUR	0.75
GBP	0.50
INR	8.00
JPY	0.10
NZD	2.50
USD	0.25

Rates are taken on 12th of each month.

Oil price



110.17
December 2012

110.3
January 2013

Values are taken on 12th of each month.

Herrenknecht acquires vehicle manufacturer

Germany Herrenknecht took over the French manufacturer of tunnel supply vehicles, Techni-Métal Systemes SAS (TMS) in Livron, in early December, the company announced recently. The tunnelling giant stated that by acquiring TMS it is expanding its portfolio of all technical equipment and services around TBMs. Herrenknecht stated that some 20 engineers and specialists from TMS are bringing their knowledge in engineering, design and vehicle assembly with them.

In addition, Herrenknecht will offer its customers service and supply of spare parts for these tunnel supply vehicles, which can be used to transport personnel and material both in tunnel construction and in mining.

"TMS offers state-of-the-art products, which are indispensable for modern tunnel construction, because quicker tunnelling performances must go hand in hand with very efficient transport systems in the back area", says Gebhard Lehmann, vice chairman of Herrenknecht's Board of Management. "As a full-service provider in tunnel construction we are now able to offer our customers an even broader range of additional equipment as integrated solutions."

A cooperation between Herrenknecht and TMS has existed since 2007.

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LU CELEBRATES 150 YEARS

London kicked off a year of celebrations with the 150th anniversary of its metro system. The UK capital's celebrated mass transit system, London Underground (LU) is the oldest such network in the world, and was the most extensive until recent extensions by Shanghai and Beijing in China, and Seoul in South Korea.

The first ever LU train journey was a 3.5 mile (5.6km) trip from Paddington to Farringdon station, which took place on 9 January 1863. One of the chief celebrations of the anniversary involved a recreation of this maiden journey with a restored steam train built over 100 years ago.

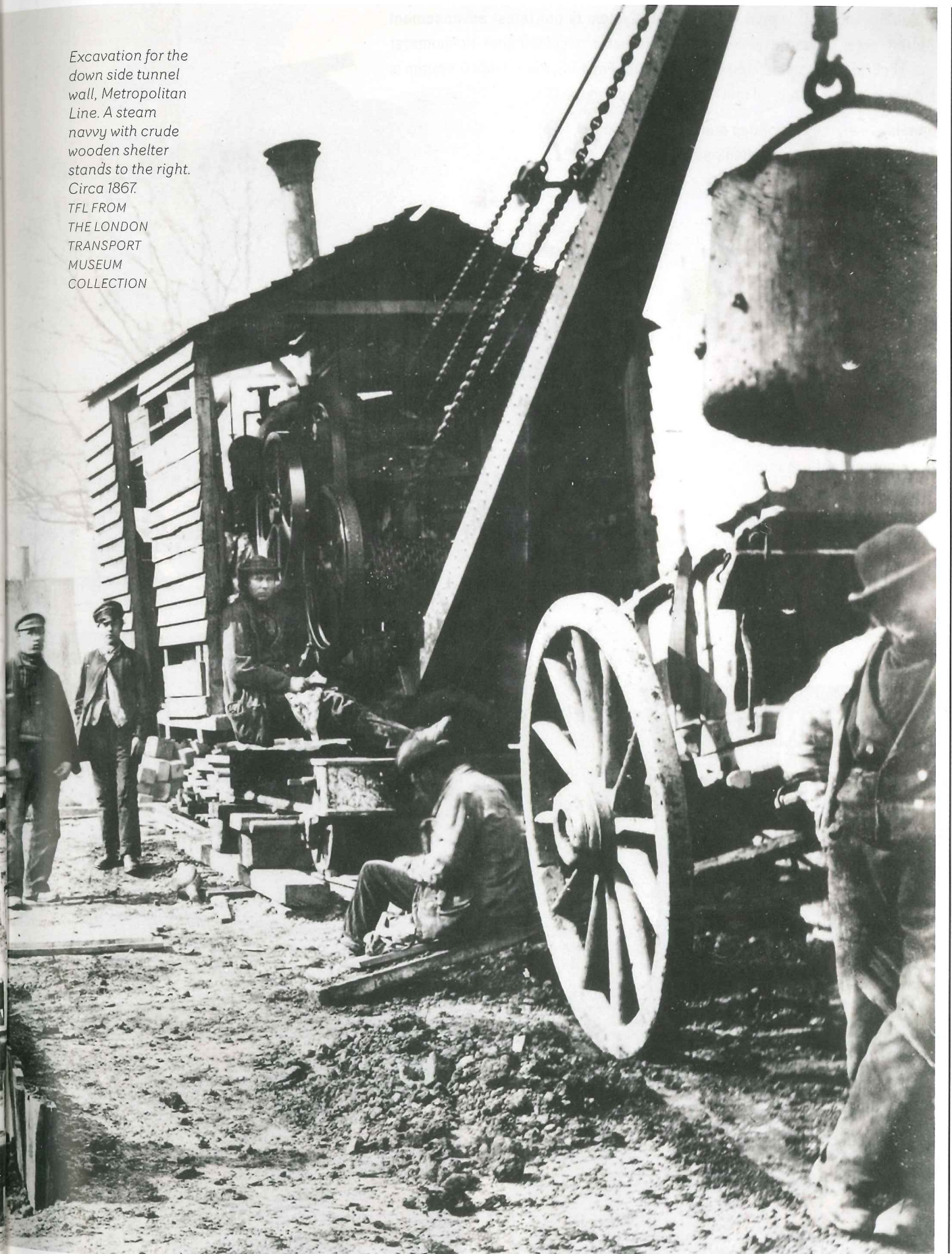
LU's parent company Transport for London (TfL) operated the service on 13 January 2013 and the 20 January 2013. The newly restored Met Steam Locomotive Number One, the last locomotive to be built by the Metropolitan Railway, pulled Met Railway Jubilee Carriage Number 353, the oldest operational carriage.

The London Transport Museum will also be running a poster art exhibition, hosting talks, holding theatrical events and more for the occasion. For more information visit www.ltmuseum.co.uk

See the Editor's Comment in *Tunnels International* January 2013 for more on the fledgling years of LU and the problems that beset a metro with no example to follow



Excavation for the down side tunnel wall, Metropolitan Line. A steam navy with crude wooden shelter stands to the right. Circa 1867.
TFL FROM THE LONDON TRANSPORT MUSEUM COLLECTION



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HOLD THE LINE

Maurice Jones points out that modern surveying methods now rely heavily on electronic instruments and automatic data collection and analysis through advanced software packages. While these should not detract from understanding of basic principles, the potential for time and staff savings, plus increased understanding of the objects being surveyed, is substantial

THE ADVANTAGES of modern surveying methods and systems are particularly evident in underground construction where the environment can be particularly troublesome for the surveyor, sometimes with a lot of work to do in a small space for which other functions are competing. ■

Maurice Jones
 With decades of experience in tunnelling, Maurice is also a former editor of *Tunnels*



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Most will be familiar with laser-based instruments and guidance systems used as references for accurate tunnel alignment and levels in guiding TBMs, roadheaders and blasthole drilling patterns, but it is how these can be set up accurately that is vital to the correct location of the required excavation. In addition, surveying can perform the following functions, to name a few:

- Checking that surfaces are within design tolerances including over or under excavation, correct lining thickness, and non-interference with the operational 'envelope';
- Support setting out tasks including rock bolts/anchors, pipe roof, and formwork positioning;
- Monitoring of any movement of excavation surfaces and the geotechnical instruments;
- Accurate installation of any installed services, both temporary and permanent types;
- Checking positions after any major incident, such as in an accident investigation procedures;
- Generation of data records and reports for construction progress and final build for commissioning and handover.

In addition to increased accuracies, modern surveying methods can, if correctly managed, also achieve economies through 'one-man' surveying instead of two- or three-person teams, and the transfer of routine, usually small-scale, set-out and similar tasks to machine operators and skilled miners.

DESIGN SET-OUT

Over the years Amberg Technologies has developed a range of software packages for both survey office and in-tunnel use. The TMS suite covers functions such as setting out, comparison of design and actual profiles, using total stations within TMS Office. TMS Office also includes various levels of scanning functions using various proprietary scanning instruments. Finally 'Amberg Tunnel' covers geotechnical functions using total stations or special geotechnical scanning instruments.

Amberg Technologies recently entered into co-operation with Poltinger Precision System (PPS) for TBM guidance set up. The project can be defined within the TMS Office package, followed by direct export of the axis and theoretical sections to the PPS system for subsequent TBM reference and guidance. More features from this collaboration are promised for later.

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Initial set-up for major alignment and profile measurements from control stations still requires professional surveyors, although procedures are now usually much less laborious than in traditional surveying methods, and may require less manpower. Subsequently, setting out tasks may be transferred to other skilled personnel if the procedures can be easily understood and/or are repetitive.

The complex excavations for Lot A2 of the Linth-Limmern pumped storage power plant in Switzerland includes three rock caverns. Contractor Arge Kraftwerk Limmern, has been using the Amberg survey software packages TMS Profile, TMS Setout and TMS Tunnelscan. In this work TMS Setout was also employed for the rapid and efficient setting out of rockbolt positions as well as verifying the cavern profiles with TMS Profile.

The contractor's surveyor, Bertrand Jeanguenat says, "Using TMS Solution we can evaluate the data direct at the tachymeter. This puts us in a position where we are quickly able to react to profile discrepancies, thereby avoiding construction delays and saving costs. The TMS Setout surveying application also simplifies the setting out of rockbolts."

Amberg's enhanced Setout Plus software is designed to provide a 'virtual' surveyor to the tunnelling crew to carry out setout duties once the tunnel surveyor has set up the system in design mode. Subsequent setting out by the tunnelling crew uses the total station as a motorised tunnel laser, without calling on the project surveyor. In fact on-site surveyor requirements can be reduced by as much as two thirds. The total station in the production mode the total station offers predefined automated functions. Meanwhile the instrument is under continuous surveillance of its position, and can be operated by remote control. It also has log files for subsequent quality control checks.

SCANNING

One the major advances allowed by the use of laser distance measurement combined with powerful software has been the possibility for mapping a wide range for surfaces for location. Multiple short-interval sightings produce a 'picture' of the object being scanned, such as the surface of a tunnel perimeter. Using any of the major scanning instruments



Above and left: Modern surveying methods can, if correctly managed, also achieve economies through 'one-man' surveying instead of two- or three-person teams

Amberg's TMS Tunnelscan software data can produce a 3D view, which can be used for comparison of measured scan data and the theoretical tunnel model. In practical terms this can translate to the planned and actual excavation, and also the inner surface of lining support and any reinforcement.

The latest instrument partner of Amberg TMS Tunnelscan is the Faro Laser Scanner Focus 3D. Under the agreement Faro is providing TMS Tunnelscan packages with the Laser Scanner Focus 3D for tunnel construction. Amberg can also offer TMS Tunnelscan, (together with the APM instrument position method as below) with the Leica HDS7000 and Z+F Imager 5010 instruments as well as its own Amberg Profiler 5033. These three instruments have very similar specifications whereas the Faro Focus 3D is lighter, with a longer lasting power supply, although smaller operational ranges.

Using Amberg's own Profiler 5003, scanning can target up to 500,000 points per second; its speed giving a major advantage in not obstructing other tunnel works. Each setup typically needs less than two minutes for a full scan of up to 12.5 million points. In conducting an 'as built' survey TMS Tunnelscan can be used with the Amberg Positioning Method (APM) referencing back with a total station or TMS motorised laser. This can achieve a performance of 130m per hour in one-man operation.

APM is a multi-point alignment method that can be

related back to the high-precision survey methods developed for the installation accuracy requirements at the turn of the century for linear colliders. This geodetic survey solution to avoid problems with variable light-beam refraction was developed by the Deutsches Elektronen-Synchrotron DESY at Hamburg with the Stanford Linear Accelerator Center (US), the Bauhaus-University Weimar (Germany) and the Technische University Dresden (Germany). The accuracy requirement for DESY installation was 0.5mm transverse and 0.2mm vertical over a range of 600m. With the development and availability of commercial scanning instruments, applications have now become widespread for surface applications such as coastal profiles as well as underground applications in tunnels and mining. Multi-disciplined surveyor company Six-West of Belfast, Northern Ireland, recently undertook a detailed topographic survey of a gold mine at Curraghinalt at the request of Canadian exploration company Dalradian Resources. Six-West suggested a full, high-definition laser scan of the mine to produce the highest possible level of detailed topographic information. This would give a 3D model allowing shareholders and potential investors the opportunity to 'virtually' walk through the mine from their desktops. Six-West director Paul McCabe explained that the surveyor selected the Leica C10 HD scanner (now superseded by the Scan Station P20) over the Trimble Faro due to it being more suitable for wet sections of the

mine. These two scanners are the most popular today. McCabe explains, "These instruments measure a full 360-degree array at a rate of up to one million points per second. The resulting point cloud is a complete 3D model of everything within range of up to 100m of the instrument to a user-defined resolution of anything from 2mm by 2mm upwards."

Describing the procedure McCabe says, "The C10 was set up at intervals of about 50m for the full length of the mine drives, totalling about 20 set-ups. Each scan took around ten minutes and was related to survey control stations that Six-West had previously installed, and related to Irish Grid and Ordnance Survey Datum using a Trimble S6 total station. Leica Geosystems HDS Cyclone software was used to reference and combine all the scan data."

The Cyclone software, which offers a wide of set of process options for 3D scanning from point cloud observations, in this case providing final output in AutoCAD dxf, ASCII xyz and as a 'fly through' video in avi format.

Another useful facility of scanning is available through the intensity of the laser reflection. Explains Paul McCabe, "The lighter the colour of the object scanned, the better the return. As a result, the scan data also picked up important painted up references on the sidewalls such as changes and markers indicating particular geological intersections." McCabe also points out that scanning using a remote-control, unmanned vehicle has safety advantages. In mining it can provide high-resolution surveying of open stopes or, perhaps in tunnelling, particular hazardous areas of unstable ground such as fall cavities.

Within a wide range of instruments for all types of surveying duties Leica offers two series of scanning instruments. The ScanStation P20, mentioned above, is the top of the range ultra-high-speed scanner that gives a high level of detail at long ranges (up to 120m). Other ScanStation models are the C10 and entry-level C5.

The other Leica series is the High-Definition-Surveying (HDS) instruments using phase-based technology to achieve high-speed, detailed results. Phase-based instruments use multiple laser transmissions, the return signals of which are differentiated by methods such as wave-length/colour filters. The Leica HDS6200 and HDS7000 are particularly recommended for tunnel work.

The specialist Amberg Geotechnics software produces a 3D view of the tunnel model input as the basis for



Above: Basic principles should not be neglected

subsequent collection of geotechnical data by limited scanning as below.

GEOTECHNICS

In addition to setting out and alignment checks, surveying instruments can now be used as a means of collecting data for geotechnical monitoring. Recently introduced software from Amberg Geotechnics, for example, allows efficient and cost-effective observation and evaluation of deformations of the excavation or support, and of settlements. Of course it can also be used for recording installation and maintenance of instrumentation such as extensometers. The Amberg system can accept data from a wide range of instrument outputs from different suppliers, with automatic point allocation without the need for separate inputs. The data can be used to produce tunnel images in 3D over several construction stages.

Geotechnical reports are produced with defined filters to give fast evaluation to identify hazardous areas. One advantage of this and other scanning procedures for project supervisors is the possible elimination of numerous spreadsheets from which useful data has to be extracted or highlighted.

Amberg recently announced a new capability for handling images produced by the Leica TPS within its office software. This integrates a facility for photographic-type image storage on the Amberg database for recovery when required. Oliver Schneider says, "Pictures in the tunnelling world are sometimes useful for geological mapping and for evidence purposes." The facility can therefore be used to accurately locate geological features or rock anchor installations (perhaps before being covered up by lining support) or to show the layout as well as location of items following a hazardous incident.

Use of motorised total stations on the surface is now common to check on any movements caused by settlement or geotechnical anomalies at pre-set stations. It would also be possible to scan critical structures for any displacement. Many organisations such as VMT in concert with ITC Engineering (IRIS system) are striving to perfect the integration of data so collected with that generated by tunnelling operations, chiefly of TBM operational feedback such as excavation rates, or grouting operations. Data can be compared on both time and location basis so that project engineers can have a better understanding of the ground and surface reactions to tunnelling operations, be warned of any hazardous situations by pre-set alarm limits, and be able to better suggest action.

500

The number in thousands of points per second that Amberg's Profiler 5003 system can target

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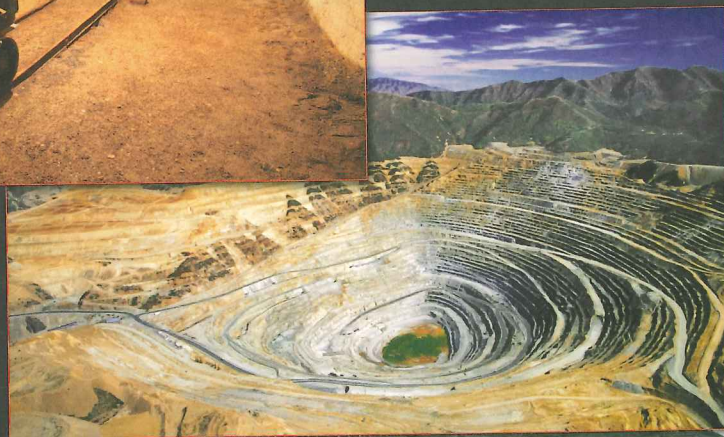
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The west metro expansion in Helsinki

POINTING NORTH

Alex Conacher speaks to Ari Laitinen, Sandvik area manager for Scandinavia for his impressions of the quirks of operating in Europe's northern extremity

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



THE REACTION time is getting shorter from contract award to delivery, says Ari Laitinen, Sandvik area manager for Scandinavia. "It is busy right now, as is Latin America, one of my other regions, and we are noticing this shorter notice period. If you don't forecast far enough, taking risks, then you are too late. It is not enough to just react to orders."

Laitinen gives some major projects, "Lansimetro [Helsinki's western metro extension] requires 3Mm³ of excavation. There are two 14km tunnels and seven stations over about 10 contracts. This is a major one for us, of around 20 drill and blast rigs on site, we have about 15. A significant project in Finland, where we are still seen as the 'local' manufacturer.

"In Sweden of course are the tunnel works around Stockholm, notably the Citybanan with two 6km tunnels. We've faced heavy Atlas Copco competition on this one."

Laitinen adds that Norway is more difficult. The real strength of the Norwegian tunnelling industry is not measured in mega projects, but the sheer volume of excavated material. Its multitude of road tunnels under 3km.

COMPARING PACKAGES

In terms of the companies attracted, Finland gets less of an international interest. "There is a particularly high level of rock excavation experience and proficiency here," says Laitinen. "The price is lower here than elsewhere in Scandinavia. Also compared to Sweden for example, contract packages tend to be smaller – allowing smaller, local companies to bid for entire contracts. Installation work is typically in a separate contract. This all serves to make Finland less attractive to large companies such as Strabag, from Germany, Austria and the rest of Europe."

The contract culture in Sweden is particularly admirable to Laitinen, "As the contracts are more complete there, the client involvement is stronger. It's almost a more civilised way of doing things; everyone is pulling towards the common good – the completion of a project with a high quality end product. There is less of a focus on the price."

"Norway is probably the most active country, with correspondingly the highest price level. They excavate 4.5bn cubic metres in a typical year. In 2012 I think it may have been closer to 6bn. This is mainly for highway work (3.3bn) with some rail and some hydropower. An influx of foreign contractors is currently driving the price down."

In terms of the business culture, Norway is more closed and does things its own way, Laitinen explains. "But in general it probably lies somewhere between Sweden and Finland."

NORWAY BY THE NUMBERS

Norway requires an incredible amount of data collection compared with the other countries. "This is for legal repercussions," says Laitinen. "In the event of a collapse, it is particularly important in Norway to be able to go back through the data during the investigation. There is also a greater requirement to have all of the geology observed to create enormous databases."

BARRIERS TO ENTRY

Language is a major barrier to entry into the Scandinavian market. All documents are written in the vernacular, which is a particular problem for Finnish, which is not a widely spoken language, and is also particularly difficult for English speakers. But similar difficulties exist in Sweden and Norway, and of course this is not uncommon across the world.

"Then there are the local habits and knowing how to act," says Laitinen. "Some newcomers are learning quickly, while some have to pay for the lesson."

4.5

The normal annual excavation material quantity in billions of metres cubed. The figure was perhaps closer to six in 2012

For example, there are ways of dealing with customers that have to be observed. In the larger projects in Finland, for example, client supervision is very intensive, with project criteria laid out carefully and precisely in documentation. There are many worksite meetings.

"In Sweden there is more discussion over the documents (again, very civilised). And Norway is somewhere in between."

FINNISH INNOVATION

Finland has some of the hardest, most stable (Precambrian) geology in the world. This would make it ideal for tunnelling. But the country is flat, with no great mountain ranges that it needs to drive base tunnels through like Switzerland and Austria, or incredibly steep road tunnels such as those found in the Norwegian geography.

But due to the rock – which Laitinen describes as uniquely hard – incredibly precise excavation is possible. This has led to a kind of underground artistry developing, where cavern walls are left without a concrete lining, leaving rock showing to the public after the structure enters service.

This is good for the unusually wide range of facilities the Fins locate underground. Whereas the other Scandinavian countries mainly see tunnelling from infrastructure projects, Finland gets more unusual client demands. These include car parks, swimming pools and cross country ski courses.

Finland has around half a dozen such 'hihtoputki', literally translated as 'skiing tunnel'. For other installations, such as car parks, heating is easier as the underground base temperature is between 7-8°C, far warmer than the harsh Scandinavian winter. There are also data centres in Helsinki cooled by seawater in a green drive. CNN has previously reported that data centres account for up to two per cent of global energy consumption.

Regular readers are probably familiar with the Helsinki Underground Masterplan. The Finnish capital sits on approximately 10,000,000m³ of planned underground space, with reservations for efficient connections and longer term, phased projects. Laitinen adds, "Geothermal energy too is booming. Even small wells for private housing, and the efficiency is always increasing. In general, this variety in the purpose of underground construction is common in Finland."

Another unique project in the country is the spent nuclear fuel repository Onkalo, which translates literally as a kind of hole in the ground – and not as the more exciting 'Hiding Place' of the related documentary 'Into Eternity'.

Although currently in a study phase, part of this has involved excavation of a 400m-deep rock characterisation facility. Client Posiva started the approval process in 2012, but a law had already been passed requiring all Finnish nuclear waste to be disposed of in Finland, so a solution will be necessary. The final disposal containers and caverns will require a design life of tens of thousands of years.

POLITICS

In terms of the political situation, the funding is still available despite the global downturn and numberless European crises. "Norway constructs as much as the labour market can handle," says Laitinen. "The funding there is not the limiting factor."

"Sweden is in a fairly similar situation, while Finland has the weakest funding position right now. There's still an effort in Finland to keep workflow and annual excavated volume consistent to maintain knowledge people."

CONCLUSION

Laitinen adds, "The business follows general economic trends, boom then recession. I have seen better, and I have seen worse years, but I am quite optimistic. You have to be optimistic"

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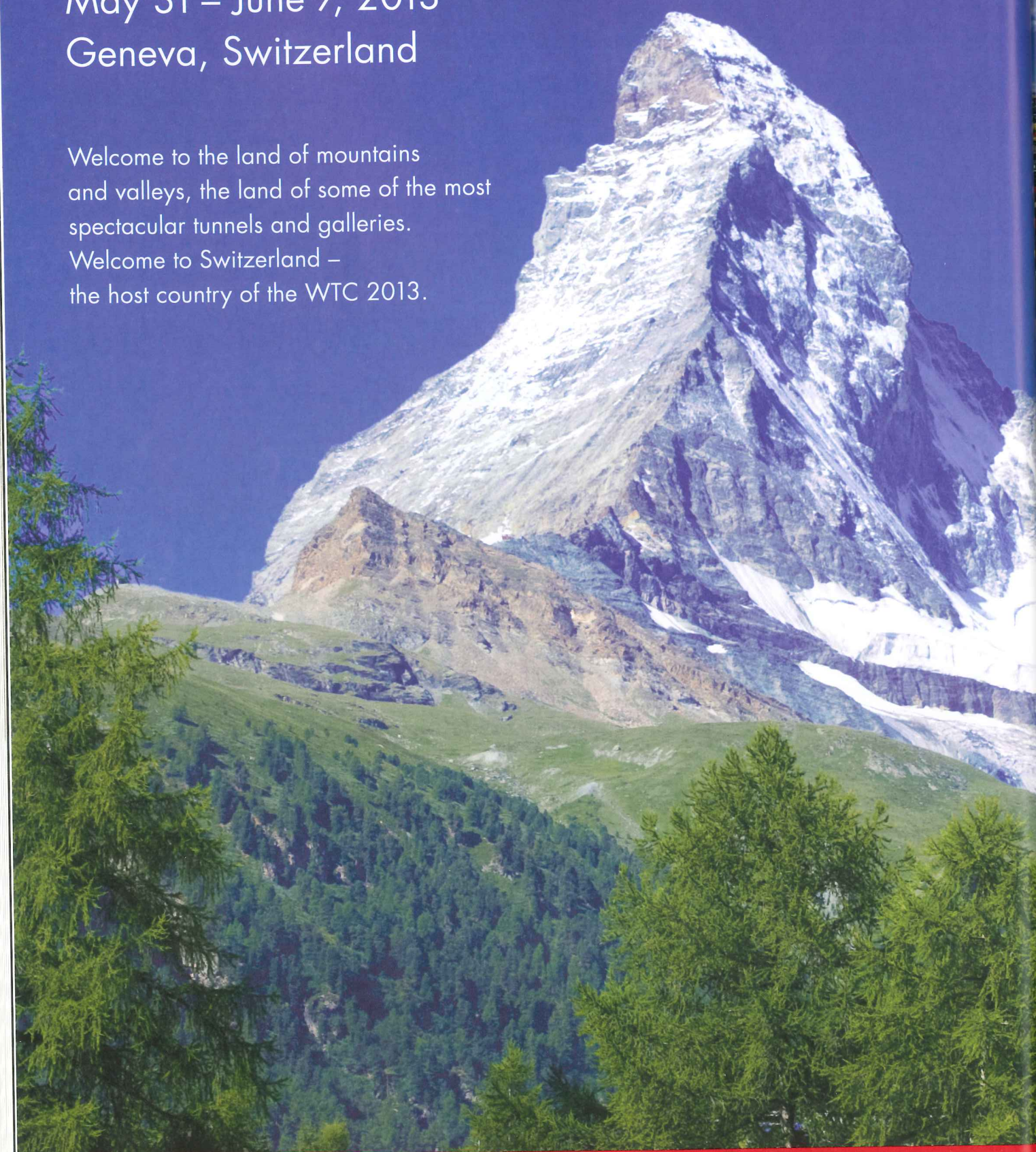
Key

- | | | |
|---|--|---------------------------------------|
| 1. Fehmarnbelt fixed link | 15. Kvis highway tunnel | 30. Norralanken |
| 2. Asen road tunnel | 16. E-6 Drovebanen | 31. Vastlanken |
| 3. Jondal road tunnel | 17. Ball Deceit Skaret road tunnel | 32. SKB Nuclear Storage Facility |
| 4. Vaagstrand tunnel development | 18. Bergen light rail system | 33. Trafikverket |
| 5. Vestfold railway line | 19. E39 Harangen to Hogkjolen Road: Harangen to Halsteinbrua Section | 34. Kiruna mine development tunnel |
| 6. Ulven-Sinsen Road Expansion | 20. Vang road tunnel | 35. Hallandsas Ridge Tunnel |
| 7. Halsoya to Leirosen road tunnel | 21. Lansimetro | 36. Norrstrom metro tunnel |
| 8. Arendal underground parking facility | 22. E18 Koskenkylä-Kotka Motorway | 37. Stockholm Citybanan |
| 9. Strindheim road tunnel | 23. Onkalo spent nuclear fuel store | 38. Bjassholmen rail tunnel |
| 10. Talvik road tunnel | 24. E18 Hamina Highway Bypass Upgrade | 39. Malmo mixed use concert hall |
| 11. Losmasse rail tunnel | 25. Vantaa Ring Rail Line | 40. Kroksberg rail tunnel |
| 12. Brokke hydropower expansion | 26. Leppavaara Ring Road I development | 41. SCC 'traffic circles' development |
| 13. E-18 Motorway | 27. Copenhagen Cityringen | 42. Soderstrom tunnel |
| 14. Vatne-Skreppenaset Tunnel | 28. Aarhus Harbour Tunnel | 43. Sodermanland bypass motorway |
| | 29. Nordhavn Branch Line | 44. Stockholm submerged tunnel |
| | | 45. Copenhagen harbour tunnel |

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COPENHAGEN COPEs

Alex Conacher speaks to **Guy Taylor**, project director of client Metroselskabet, and **Soren Eskesen**, head of Cityringen tunnelling for the client, and chair of the Danish Tunnel and Underground Works Association for this update from site, and a new project offshoot, as the first machine arrives in port and site preparations draw to a close

SITE PREPARATIONS are drawing to a close as the last of 21 worksites, Trianglen is handed over on 3 December 2012. Four TBMs from the newly partnered Seli-Kawasaki manufacturing JV are being used on the Copenhagen Cityringen, the first arrived in December, with the remainder arriving in two-month staggered shipments. Main assembly was underway as *Tunnels* goes to press, for which Seli is responsible. Mobil Baustoffe Of Germany established a segment casting factory in Sassnitz on the Baltic Coast of

Above: The historic city of Copenhagen was founded in 1167

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



Project vitals

- **Main contractor:** Copenhagen Metro Team JV: Salini Costruttori, Tecnimont and Seli
- **Client:** Metroselskabet
- **Ground engineering:** Trevi with equipment from Soilmecc
- **Design:** Arup, Cowi and Systra
- **Funding:** Copenhagen 50 per cent, Denmark 41.7 per cent, and Frederiksberg 8.3 per cent
- **Geology:** Quarternary sequence of meltwater sands and tills on Danian Limestone
- **Methodology:** TBM driven tunnels
- **Equipment:** Four 5.78m Seli-Kawasaki closed face EPBMs
- **Segment supply:** Mobil Bau

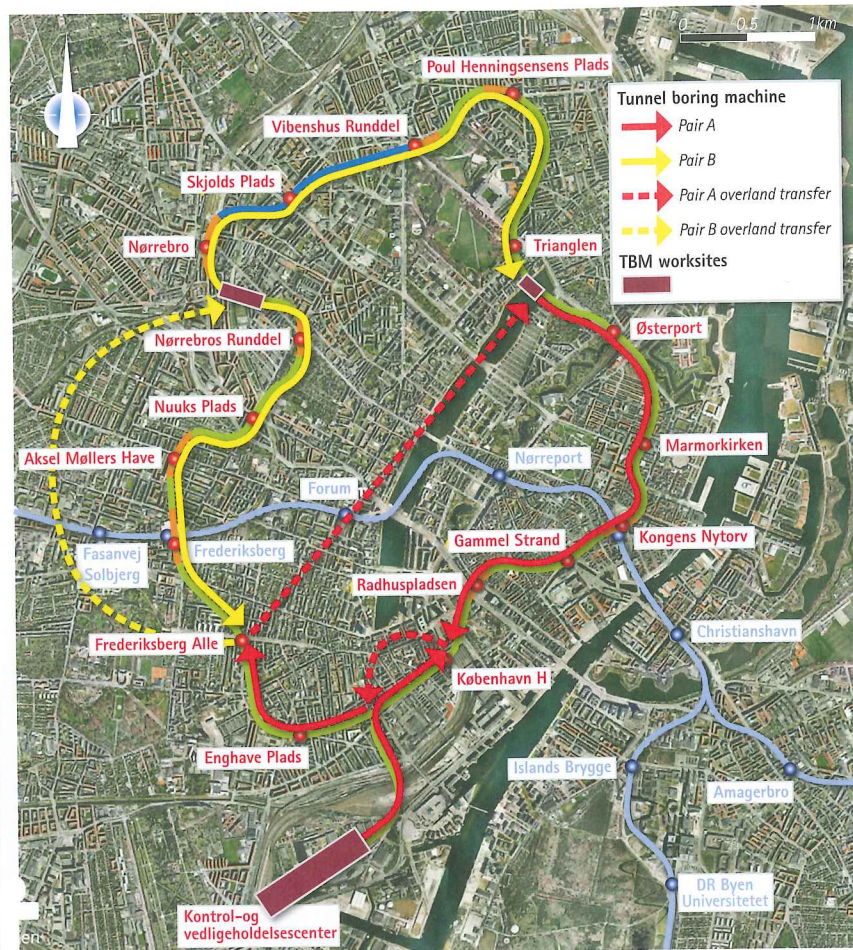
northern Germany. Segments are shipped into Copenhagen for storage prior to the start of tunnelling. Segment moulds were manufactured by Seli's subsidiary SAME, with a further nine sets coming from Herrenknecht.

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

SCHEDULE

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

When tunnelling begins following the first machine's assembly in March, the first twin drive will be executed from the Norrebro Runddel station site (see first yellow route, Figure 1). The TBMs will then be transferred by road back to Norrebro Runddel for the drive to Trianglen. The second pair (shown as 'Pair A' in red) will drive from the Kontrol-og vedligeholdelsescenter ('control and maintenance centre') site, through a bifurcation executed with a small overland transfer. The machines will then be taken by road to Trianglen



Above: Figure 1, The Cityringen alignment showing overland TBM transportation route plans

510
The value of the soon to be tendered Nordhavn Branch Line arm of the tunnelling project in USD millions

2007
The year in which work on the Copenhagen Cityringen project received a political decision to proceed

Table 1 - TBM main characteristics

Main drive	
VFD electric motor	6
Total installed power	1,200kW
Speed	0-5rpm
Maximum torque	4,790kNm at 2.3rpm
Minimum torque	2,180kNm at 5rpm
Unlocking torque	6,237kNm
Cutter head	
Excavation diameter	5,780mm
Opening ratio	30 per cent
Cutting tools	38 17-inch cutters
Maximum individual load	267kN
Copy cutter	Up to 5,880mm
(Wear detection system equipped)	
Thrust system	
Thrust rams	32 (16 by 2)
Maximum working thrust	37,000kN
Maximum total thrust	54,500kN
Articulations	
Front active articulation	30,000kN
Rear passive articulation	10,000kN

Source: Seli

Geology

The ground conditions along the alignment of Cityringen comprise a quaternary sequence of meltwater sands and tills resting on Danian limestone. The quaternary deposits are overlain by fill as well as post- and late-glacial deposits. Deposits belonging to the Selandian (Middle Palaeocene) Greensand Formation are also found locally subjacent to the quaternary deposits.

The fill layer is of varying thickness, with thick deposits found in areas with previous moats, lakes and canals, as well as old clay pits and sand/gravel quarries.

In the quaternary deposits two layers of till are observed, an upper till unit and a lower till unit, separated by meltwater sediments. Locally the two till layers constitute a contiguous layer e.g. as seen in the Frederiksberg area. The tills are typically heavily over-consolidated, very stiff to hard sandy clays.

Three meltwater layers have been identified. The upper meltwater unit is of very limited extent, the middle meltwater unit is separating the two till units, and the lower meltwater unit is mainly observed as coarse grained sediments filling erosion valleys in the project area.

Across much of the alignment the quaternary sediments are directly underlain by the Copenhagen limestone of Danian age. However, Selandian Greensand deposits are observed locally adjacent to quaternary deposits within the southern part of the alignment. The Copenhagen limestone is a fractured soft rock, which has some similarities to fractured chalk. Based

on geophysical logging, the Copenhagen limestone has been subdivided into three sub-units, upper, middle and lower Copenhagen limestone. The upper Copenhagen limestone is horizontally bedded with layers of different hardness and thickness from a few centimetres up to 1m. Flint occurs in beds of 0.2 to 0.4m thicknesses, occasionally up to 1m in thickness and can be followed continuously over long distances.

The pre-quaternary surface is characterised by meltwater erosion valleys, incised in the limestone surface. The interface between the quaternary deposits and the Copenhagen Danian limestone takes one of two forms, either more fractured than lower in the limestone (glacially disturbed) or unaffected by glacial disturbance.

The geological conditions that will be encountered by the TBMs will vary along the alignment. The tunnelling in the southern section is predominantly in the limestone, whereas the northern alignment is in glacial deposits, limestone and mixed conditions giving more difficult tunnelling conditions.

It should also be noted that although the tunnels in the southern half of the alignment are generally in limestone, often the tunnels rise as they approach or leave the stations. In several cases the tunnel next to the stations are bored within mixed face deposits with corresponding larger amounts of ground movements. This is the case for instances close to Kongens Nytorv, Radhuspladsen and København H.

to commence the main drive back to meet the first (eastern) arm of the bifurcation. The total length of the project will be 15.5km with 17 underground stations, excluding the control and maintenance centre.

New arm

It has been decided to launch a new branch of the metro off towards the city's northern port. This will run for 2.3km and will tender in Q2 of 2013. Called the Nordhavn Branch Line, it will run from Østersodgade and will link the Cityringen with a new riverside urban development by the client's sister agency, Byoghavn. The value of the new project will be DKK 2.9bn (USD 510M).

IMPACT

Cowi, Arup and Systra handled vibration analysis as well as all other design and engineering works. A local process involves an expropriation committee being appointed to decide on compensation for local residents affected by the works. This process began in 2007, with planning and design. As an example of the results of this, a main station is situated in a narrow street in front of residential apartments. The noise and vibration was deemed

Below: The EPBM is accepted in Seli's yard



sufficient for compensation to the inhabitants, but no one was re-housed.

WATER, SETTLEMENT

Taylor and Soren Eskesen, in charge of tunnelling for Metroselskabet, believe that the limestone geology of Copenhagen is well understood and should not offer too many surprises, though the shallower sedimentary layers are of course less stable (see geology box, page 29).

There are no settlement or damage criteria, and the risk is on the JV. Pre-investigation has been done with a three-stage building assessment.

"Some of the older buildings are built on timber piles," says Eskesen. "We must not lower the groundwater around these areas – if these wooden piles are exposed to air, they will [drastically] deteriorate."

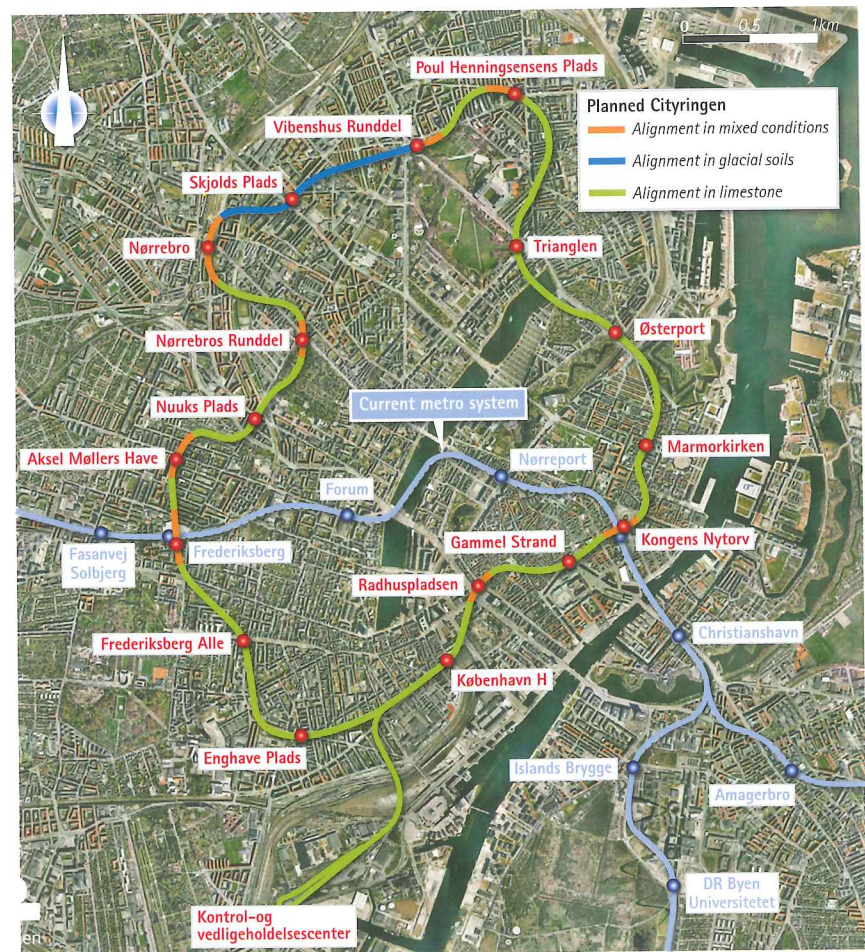
"Hence the choice of a closed face TBM for the tunnels. There is better control enabled, and we are less likely to lower the water level."

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

"The contractor has opted for secant piles down to 28m and then diaphragm walls for anything deeper. Of the 21 sites, seven have diaphragm walls. These are all part of the permanent works, while the inner lining is designed to take the water pressure."

Engineering

Trevi has been subcontracted to do the enormous amounts of ground engineering. Eskesen says, "This includes ground treatment in some areas. Trevi currently has 11 secant piling machines working at the stations and five d-wall rigs. At this time [18 December] secant



Above: Figure 2, The complete map of Cityringen stations

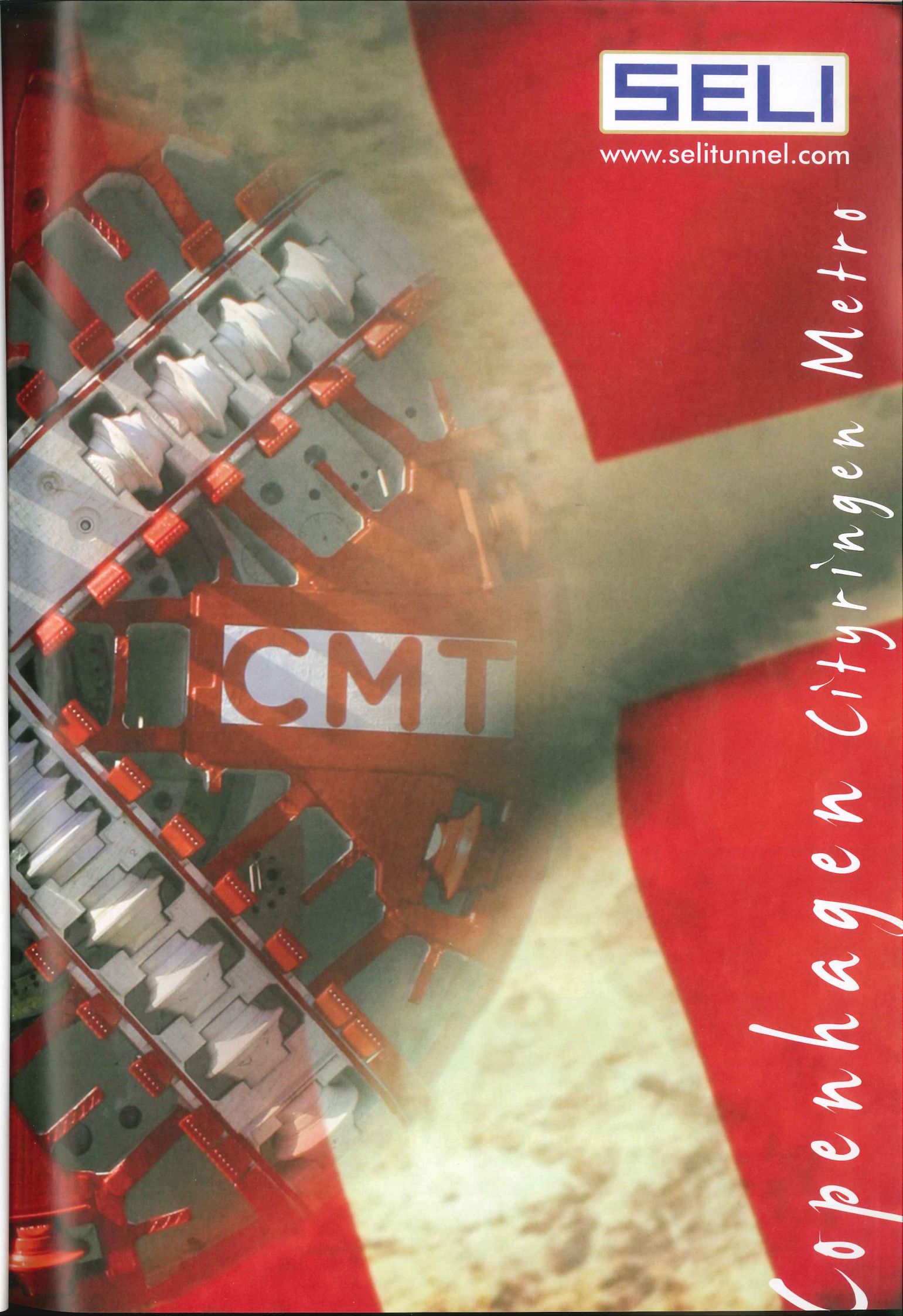
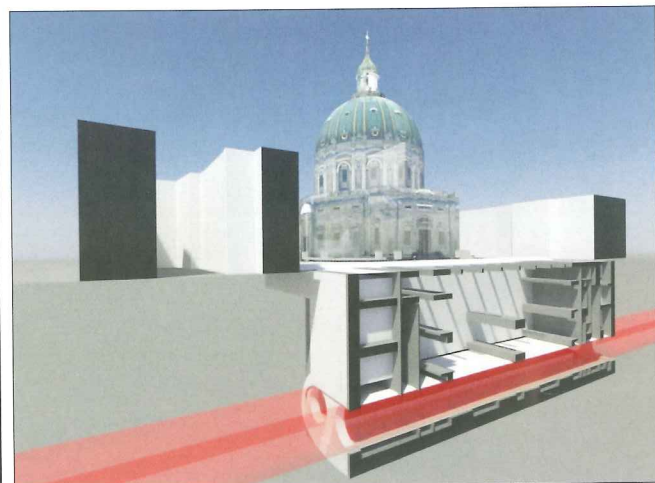
Below: Figures 3 and 4, changes in design of Marble Church Station

piling work has been completed at two stations and the roof slabs are going on."

Starter's orders

The Cityringen should open in 2018 at the end of the contract. Ansaldo is the company responsible for tunnel operation over a five-year period, and will supply rolling stock. A Ramboll-Atkins JV will oversee the railway infrastructure engineering works

■ For a detailed look at the challenges constructing Cityringen, especially the redesign of Marble Church Station, see the feature written by the contractors and client in *Tunnels International*, February 2012, pp.24-28.



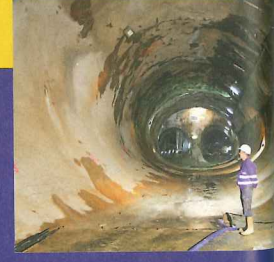
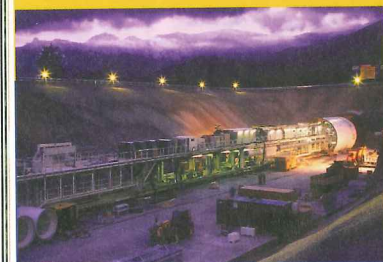
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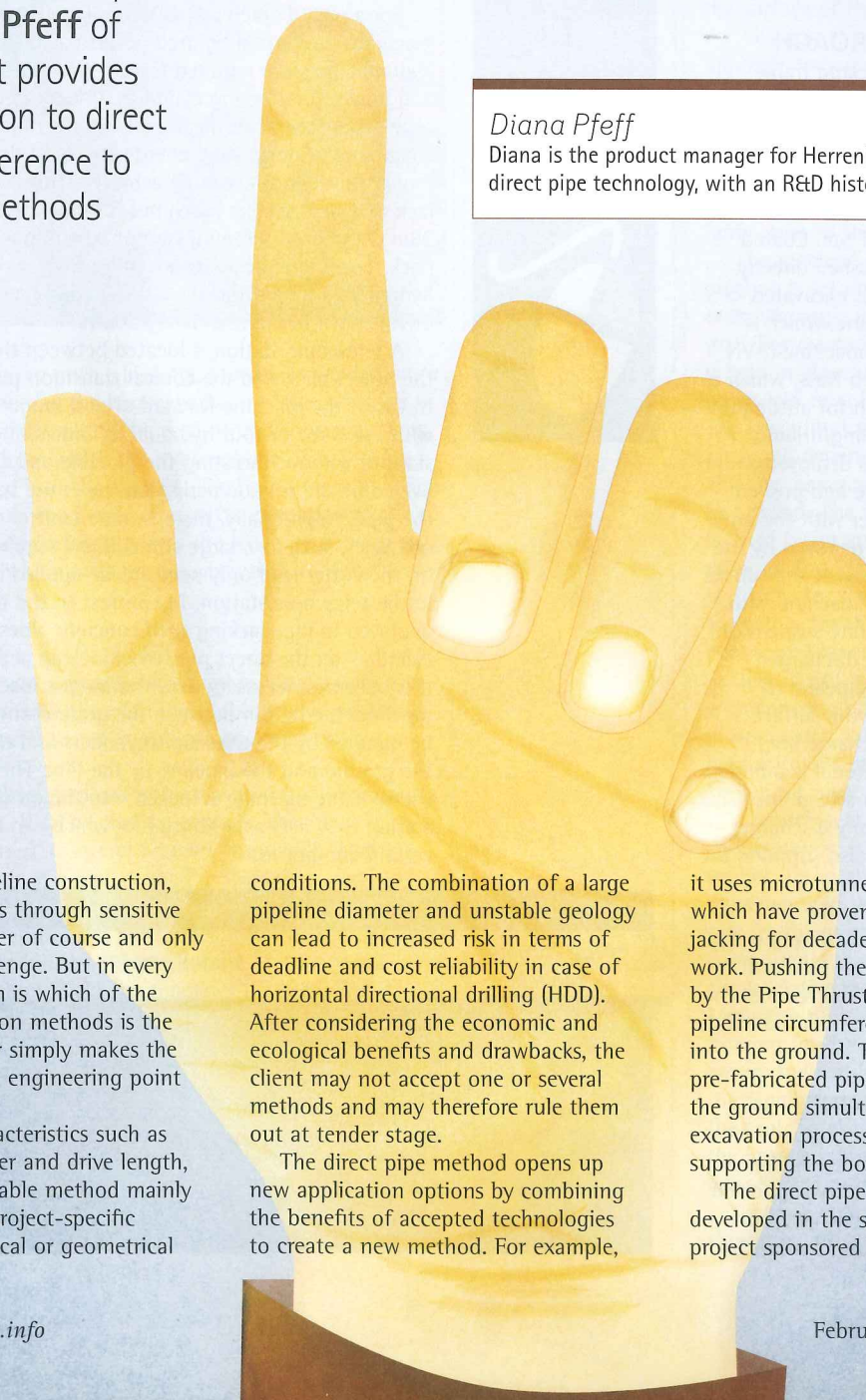
EQUAL OPPORTUNITY EMPLOYERS

DIRECT TO THE POINT

In the first of a two-part series **Diana Pfeff** of Herrenknecht provides an introduction to direct pipe with reference to alternative methods

Diana Pfeff

Diana is the product manager for Herrenknecht's direct pipe technology, with an R&D history



IN PIPE and pipeline construction, safe passageways through sensitive areas are a matter of course and only rarely a major challenge. But in every project the question is which of the available construction methods is the most economical or simply makes the most sense from an engineering point of view.

Apart from characteristics such as the pipeline diameter and drive length, the choice of a suitable method mainly depends on other project-specific parameters, geological or geometrical

conditions. The combination of a large pipeline diameter and unstable geology can lead to increased risk in terms of deadline and cost reliability in case of horizontal directional drilling (HDD). After considering the economic and ecological benefits and drawbacks, the client may not accept one or several methods and may therefore rule them out at tender stage.

The direct pipe method opens up new application options by combining the benefits of accepted technologies to create a new method. For example,

it uses microtunnelling machines, which have proven their value in pipe jacking for decades, for excavation work. Pushing the pipeline is handled by the Pipe Thruster, which grips the pipeline circumferentially and pushes it into the ground. This means that the pre-fabricated pipeline can be laid in the ground simultaneously with the excavation process, thus permanently supporting the bore hole.

The direct pipe method, which was developed in the scope of a research project sponsored by the German Federal

Ministry of Education and Research (BMBF), was successfully deployed for the first time in 2007 for a Rhine crossing in Worms, Germany. Since then, the individual process components have been continuously improved and adapted to reflect increasing requirements. To date, 18 projects have laid a total of more than 9km of pipeline in Europe and the US (status June 2012). The pipeline diameters vary between OD 30in (762mm) and OD 56in (1,422mm) with a maximum drive length of 1,400m.

The now established process is characterised by the fact that it is suitable for direct laying of larger diameter product pipes. In specific project framework conditions, direct pipe offers benefits compared with older established laying methods, and is thus a useful alternative in many cases.

FUNCTIONAL APPROACH

Comparable with the jacking frame used for standard pipe jacking with short concrete pipes, the Pipe Thruster acts as the thrust unit in direct pipe. It hydraulically grips the pre-fabricated and outlaid pipeline and pushes it into the ground in strokes of 5m. Coated product pipes can be pushed directly. The required bore hole is excavated by the direct pipe machine, which is based on an AVN micromachine (AVN is Automatischer Vortrieb Nass, which is the German abbreviation for automatic slurry supported tunnelling/drilling process). The machine is deployed at the front end of the pipeline and pushed into the ground together with the pipe. The excavated material removed by the slowly rotating cutterhead at the tunnel face is mixed inside the machine with the drilling fluid (bentonite suspension) and then fed through a discharge line through the entire pipeline to the separation plant on the surface (through a separate discharge line). After treatment, the material is pumped back into the circuit via a feed line. The drilling fluid thus not only discharges the excavated material but also supports the tunnel face.

The overcut created by the cutterhead, approximately 50mm radius, is filled with high-viscosity lubricant (bentonite suspension). This reduces the friction between the bore hole wall and the laid pipe.

DIRECT PIPE MACHINE

The slurry supported direct pipe machine works roughly in a similar way to a conventional slurry supported microtunnelling machine (AVN), but differs in terms of length. To allow for

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a curved motion of the machine and the trailing pipeline in the culvert path, the machine is equipped with two to three backup pipes. The fact that all of the joints in the individual backup pipes are articulated and tight connected to resist pulling force, ensures optimum steering capability of the machine. An additional benefit is the fact that the machine can be pulled out with the pipeline, again with the Pipe Thruster, in a case of emergency. In the scope of project planning work, the machine's cutterhead is adapted to the geological conditions of the project. If boulders or rock are anticipated en route, disc cutters can be deployed in addition to the cutting knives. Installing a cone crusher behind the cutterhead helps to substantially extend the AVN machine's range of applications in geologies with coarse gravel, cobbles and boulders. The crusher basically uses the same principle as a coffee grinder. Stones are ground until they pass through the round openings in the inner cone, the last stage of the screen-type grain size limitation. This prevents blockages in the slurry line, or at least reduces them to a minimum. The conservative upper grain limit resulting from these two crushing mechanisms is 30 to 40 per cent of the cutterhead diameter.

For a pipe diameter of OD 40in (1,016mm), direct pipe machines have an integrated power pack. The unit creates the hydraulic pressure required to turn the rotating cutterhead and power the steering cylinders. It is located in the backup pipe behind the cutterhead and the steering cylinders. The advantage of generating energy locally in this way is that longer drive lengths can be achieved. However, due to the lack of space, smaller machines for pipeline OD of 28in to 38in (711mm to 965mm) cannot be equipped with a power pack. The hydraulic losses resulting from a therewith necessary hydraulics supply from the control container thus restrict the drive length to approximately 300m.

A telescopic station is located between the backup pipe with the power pack and the conical transition piece. It is possible to thrust the machine forward after a longer period of standstill with the three or four hydraulic cylinders of the telescopic station, without thrusting the pipeline and thus needing to overcome the friction acting on the entire surface area of the pipe. Additionally, there is more control over excavating obstacles, such as a large stone, if the required contact pressure on the cutterhead only needs to be applied by the cylinders in the telescopic station. In contrast to the telescopic station deployed in pipe jacking with concrete pipes, the telescopic cylinders on the direct pipe machine can act in both directions. If it becomes necessary to withdraw the machine with the pipeline, the friction between the ground and the machine can be handled by the telescopic cylinders and the friction between the ground and the pipeline by the Pipe Thruster. This can be useful if the machine is locked into the ground. The telescopic station thus acts as a safety tool which can be deployed under certain conditions.

Table 1 - Characteristics of the three different Pipe Thruster models

Pipe Thruster Models	HK300PT	HK500PT	HK750PT
Max. push and pull force (in kN / tonnes)	3,000 / 300	5,000 / 500	7,500 / 750
Clamping diameter (in inches = ")	Maximum 36	Maximum 48	Maximum 60
Attack angle (in °)	0 to 15		
Weight (in tonnes)	40	53	78

Source: ICD Research Industry Survey 2011



Above: Pipe Thruster HK750PT anchored on the surface with deployed machine AVN800A and 42" pipeline



Left: Machine operator's work place set up

The transition piece onto which the pipeline is welded has a conical shape. It reduces the larger diameter of the machine to the smaller pipeline diameter. The conical transition piece has a lubricating ring from which the main volume of bentonite lubricant is pumped into the overcut. The built in rear bulkhead hermetically seals off the machine from the pipeline and the slurry lines it contains. This separates the machine components from the pipeline, which can improve operational safety in case of leakages.

PUSH UNIT PIPE THRUSTER

The Pipe Thruster was originally designed as an auxiliary tool for the pipe pull-in with the HDD method (installed on the pipe-side). The Pipe Thruster's applications are as follows:

- Pushing or pulling pipelines into excavated open bore holes (e.g. created by HDD) or existing tunnels. This has already been implemented in several projects worldwide. The maximum length of a pipe pushed in like this is currently some 4,000m.
- Pulling out previously laid steel pipes from the ground. This is also established in the US and Europe.
- Direct pipe method for laying pipelines (with coating if needed). Thus far, some 18 direct pipe projects have been successfully completed.

The maximum pipeline diameter that the biggest Pipe Thruster model can clamp is OD 60in (1,524mm). The clamping unit is mainly adapted by changing the clamping inserts to match the pipeline diameter. It was designed to avoid damaging the coating of product pipes, such as gas or oil pipelines. In tests at the Herrenknecht workshop in Germany, it

was demonstrated in cooperation with various gas suppliers that no damage is caused to the coating. Polyethylene (PE), polypropylene (PP) and glassfibre reinforced plastic (GRP on PE) coated pipes were tested at the maximum clamping force of the clamping unit and at full thrust force of the two large hydraulic cylinders.

The contact surface between the pipe and the clamping inserts is covered with hot-vulcanised rubber. It is designed to be large enough to minimise the pressure (3.5N/mm²) and shear forces (1.2N/mm²) on the coating.

SETTING UP ON SITE

Launch and target pits

Using the direct pipe method, the drilling route is typically an arc from the surface of the terrain, underneath the obstacle to be drilled under, to the opposite terrain surface, like in HDD. The benefit here is the simplicity of the required launch and target pits. The Pipe Thruster can either be set up and anchored on the invert of a flat launch pit, or on the terrain surface, or at least fairly close to the surface.

The machine connected to the pipeline is set up at the required entrance angle in front of the launch seal. The overbow of the outlaid pipeline is held in place with lateral booms or either laid on a launch track with rollers. The horizontal and vertical forces to be anchored depend on the entrance angle and the maximum push or pull force to be applied. The forces can, for example, be held by an anchoring frame and sheet piling or foundation piles with a depth sufficient for the geology. Table 2 shows the values for the resulting forces with a corresponding entrance angle.

Just like in microtunnelling with concrete pipes, penetration of groundwater, soil, slurry and lubrication bentonite out of the bore hole into the launch pit must be prevented by means of a launch seal. The overcut of several centimeters is sealed with a neoprene rubber. To be able to compensate for movements in the pipeline, the launch seal for direct pipe comprises two steel components that are supported to allow relative movement by a U-shaped Neoprene rubber. Guide rollers on the floating front part of the construction ensure the required clearance between the pipeline coating and the steelwork of the seal. To ensure the best possible seal, the launch seal is fixed to the pit wall at the selected entrance angle.

The soil coverage over the launch seal should be at least one or two times the

1524

The maximum product pipe size in mm that can be gripped by the largest available Pipe Thruster

machine diameter.

The direct pipe machine can be recovered without sinking a shaft. To allow this to happen, the machine and the pipeline are pushed into a pit excavated near the surface. Here, the machine can be separated from the pipeline, dismantled and transported away. If the machine is to be recovered from a shaft, a reception seal is needed. This prevents water and material from the overcut flowing into the shaft.

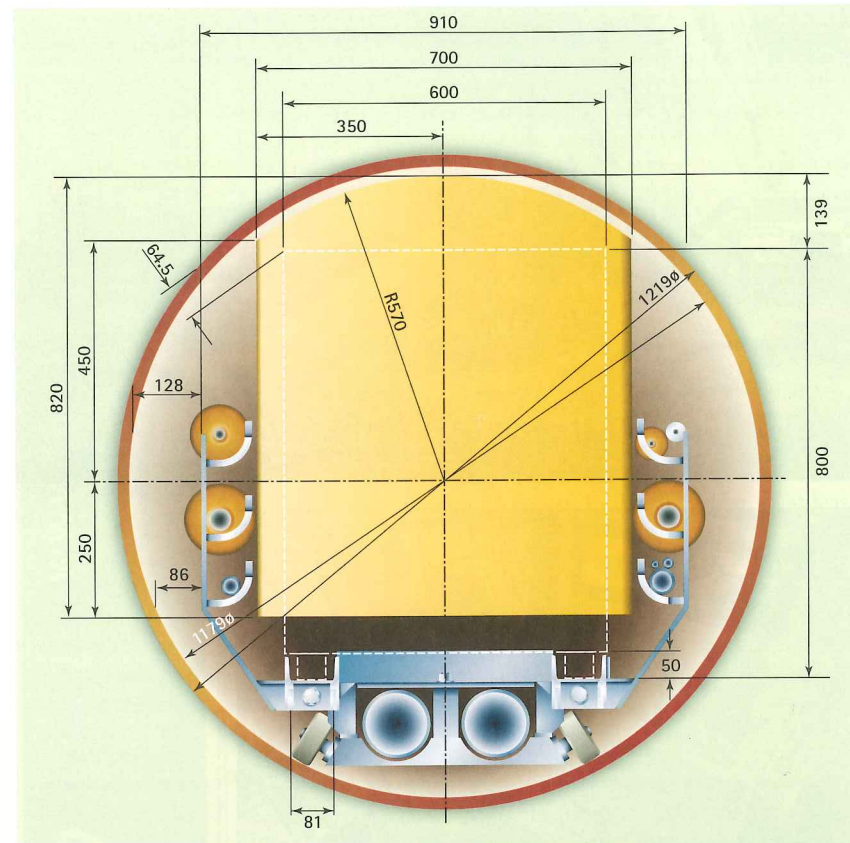
CONTROL CONTAINER

All of the process components involved in drilling and laying, such as the machine, the Pipe Thruster, pumps and navigation systems are remotely controlled from the control container. The individual functions can be operated remotely via the control panel. The information is transferred via a databus system to which all components are connected, from and to the PLC (programmable logic controller). This means that, for example, the machine's steering cylinders can be actuated, or the speed of the slurry pumps controlled. The important functions and measured values are visualised for the machine operator on multiple displays located in the control cabin. One screen displays the navigation system, another the pictures from the cameras built into the machine. To allow the machine operator to look out of the control cabin window and see the Pipe Thruster, the control container is installed next to the launch pit. The hydraulic power supply to the Pipe Thruster is provided by a power unit built into the container.

NAVIGATION SYSTEM

To allow the machine to drill precisely along the required route, and thus lay the pipeline precisely at the desired location, a suitable surveying system is needed to locate the machine. The horizontal position is determined by a fibre-optic gyroscope. The latest generation gyroscope measures continuously, thus removing the need for the interruptions to the advance, as previously dictated by mechanical gyroscopes. The vertical position is determined by an electronic hydrostatic hose balance, a simple and proven system. The navigation system is accurate to within a few centimeters.

Before drilling begins, the waypoints for the route (start/end of straights or curves) are entered in the surveying software. The machine operator sees a visualisation of where the machine is compared to the target route during drilling. By extending the three steering



Above, top and bottom: View into and cross-section of a 48in pipeline with supply lines placed on movable support structures

cylinders appropriately, the steering head can be steered. The machine moves in the changed direction, with the entire pipeline following.

SEPARATION PLANT

The separation plant separates the excavated material from the drilling mud. Screens and hydro vacuum cyclones separate the individual soil particles from the slurry suspension in various stages. If highly granular geology is anticipated, meaning a soil with a pronounced clay content, it makes sense to consider deploying a centrifuge or a filter press. The separating capability of hydro vacuum cyclones is around 40-60µm.

Table 2 - Values for the resulting forces with a corresponding entry angle

Launch angle	HK 300 PT			HK 500 PT			HK 750 PT		
	FV1	FV2	FH	FV1	FV2	FH	FV1	FV2	FH
0°	986	986	3000	1532	1532	5000	2998	2298	7500
1°	1020	967	3000	1577	1490	4999	2366	2235	7499
2°	1053	949	2998	1621	1447	4997	2432	2170	7495
3°	1087	930	2996	1665	1403	4993	2498	2105	7490
4°	1120	911	2993	1708	1360	4988	2563	2040	7482
5°	1153	891	2989	1751	1315	4981	2627	1973	7471
6°	1185	872	2984	1794	1271	4973	2690	1906	7459
7°	1217	852	2978	1835	1226	4963	2753	1839	7444
8°	1249	831	2971	1876	1181	4951	2815	1771	7427
9°	1280	811	2963	1917	1135	4938	2875	1702	7408
10°	1311	790	2954	1957	1089	4924	2935	1633	7386
11°	1341	769	2945	1996	1042	4908	2995	1563	7362
12°	1372	748	2934	2035	996	4891	3053	1493	7336
13°	1401	726	2923	2073	949	4872	3110	1423	7308
14°	1430	705	2911	2111	901	4851	3166	1352	7277
15°	1459	683	2898	2148	854	4830	3222	1280	7244

Source: Author

Smaller particles cannot be filtered by a traditional plant.

The size of the separation plant must match both the anticipated geology and the required flow rate. The slurry circuit is comparable with that of microtunnelling AVN machines. One difference is that virtually no idle phases occur in the direct pipe method. If it is possible to lay the pipeline in long pipe sections, drilling continues without interruption for several days, thus permanently feeding excavated material to the separation plant. In comparison to this, a break of about 15 to 30 minutes occurs after advancing 3m in thrusting short concrete pipes. The circuit can then regenerate during the pipe exchange. The separation plant is typically deployed in the middle (half way along) of the laid out pipe sections to reduce the required quantity of feed and discharge lines and pumps.

USE OF BENTONITE

Bentonite is a clay mineral that has thixotropic properties after mixing with water. This means that it is liquid, or has a low viscosity when in motion, and highly viscous and/or gel-like if no energy is applied. In the direct pipe method, just like in normal pipe jacking, it has three tasks. It is used to support the bore hole (at the face via the slurry suspension and in the annulus via the lubrication bentonite), for transporting the excavated material and for lubricating the annulus.

The slurry suspension is pumped in a circuit from the machine to the separation plant and back again. The rougher-grained the transported excavated material is, the higher the bentonite concentration needs to be. In finer-grained geologies it is even possible to completely manage without bentonite additive in the slurry suspension.

The direct pipe machine creates a larger annulus than a slurry machine deployed in pipe jacking with concrete pipes. It is 50mm in radius for the larger diameters, and slightly less for smaller diameters. The lubricating bentonite is pumped through a separate line through the pipeline from the surface to the end of the machine. Here it escapes at a very low, above-atmospheric pressure over openings in the cone-shaped transition piece into the annulus. The bentonite content in

the lubrication suspension is higher than that in the slurry suspension, because greater viscosity is required. The rheological properties and the volume of the injected bentonite are accommodated to the geological conditions. The annulus must be completely filled to minimise friction between the bore wall and pipe. Losses into the surrounding geology must be compensated for by increasing flow rate.

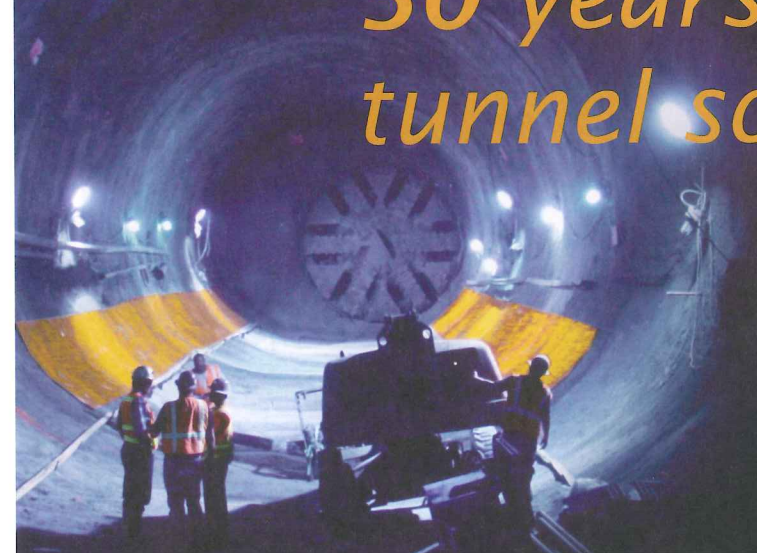
PREPARATION OF THE PIPELINE

The pipeline is laid out at the desired launch angle so that it can be easily rolled or moved in the direction of the launch pit when drilling starts. Depending on local conditions and the launch angle, it is supported either by rollers near to the ground or in a raised position. Soil can be heaped up to provide a substrate. If planning envisages an elevated overbow, side booms or cranes can be used to hold the pipeline in position. The feed and discharge lines are routed from the machine through the whole pipeline. The pipeline is equipped during the setup work. All lines are placed on movable support structures and then successively fed into the pipeline. From the end of the pipeline flexible hoses for the slurry circuit and the bentonite lubrication are routed beside the pipeline to the separation plant. The power and data cables are routed from the end of the pipeline via the laid out pipeline to the control container.

In part two of this series, the article will cover planning aspects and limits of use—including drilling diameters and lengths, thrust force and geology—and look at several case studies.

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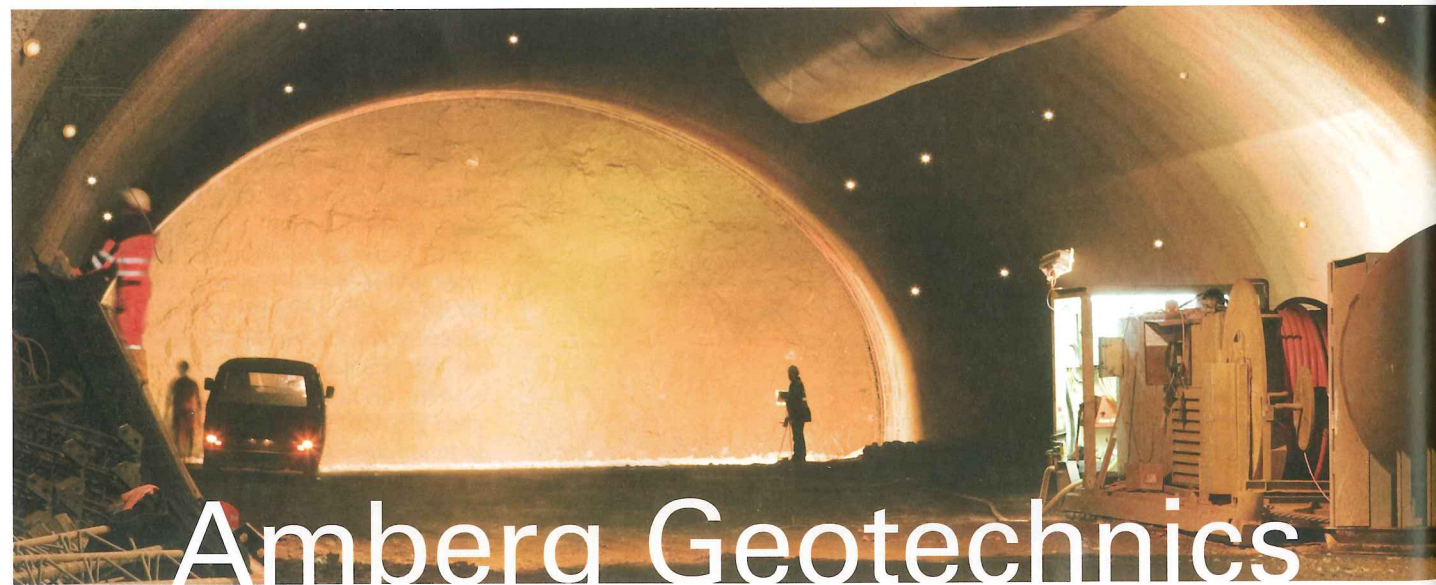
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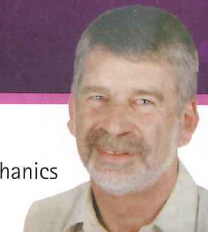
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NATM - FROM A CONSTRUCTION METHOD TO A SYSTEM

This paper by **Wulf Schubert** and **Harald Lauffer** was the basis for a presentation at the 2012 Salzburg Geomechanics Colloquium. In it, the authors cover the development of the New Austrian Tunnelling Method. In presenting this paper, Schubert, wishes for the tunnelling community to come to regard "tunnelling as a regular engineering task, and reduce the emotions and mysticism involved"

Wulf Schubert
Wulf is head of the Institute of Rock Mechanics and Tunnelling at TU Graz in Austria



Harald Lauffer
Harald is technical and contractual advisor for tunnelling at Porr Tunnelbau



THE TERM NATM was introduced by Rabcewicz during a lecture at the Geomechanics Colloquium in 1962 [1]. In this lecture, he summarises the development of tunnelling methods and insight into mechanical processes in the ground over the last decades, and points out the positive experience made with a combination of shotcrete and rock bolts instead of the traditional timber or steel supports. Building on experience and development around the world, it has been Austrian engineers who have systematically developed and applied the method. In the beginning technological questions played a major role, but it was also clear that traditional design methods were no

longer applicable. Thus it was still unavoidable to rely heavily on experience and observation. The importance of measurements for observing the system behaviour has been acknowledged, and techniques have been developed considerably further since then. Parallel to gaining more experience with the method in all kinds of ground conditions, contractual practices have also been further developed with the aim of establishing rules, which allow fair compensation of the contractor in spite of all the inherent uncertainties.

Some of the factors contributing to the success of the method are client awareness of responsibilities, appropriate site organisation, qualified engineers

and miners, practical research and education, as well as extensive exchange of experience.

HISTORICAL DEVELOPMENT

Theoretical knowledge about the mechanical processes in the ground as a result of tunnel excavation increased over the first half of the 20th century [2] [3] [4] [5] [6] [7], although in practice design was based on experience or simplified load assumptions, which mainly considered dead loads due to ground loosening (for example [8]). Based on observations of a large number of tunnels, Rabcewicz distinguishes between loads caused by loosening, 'real ground pressure', and swelling [9], and

states that the classical load theories are not applicable for the design of supports in squeezing ground.

After the Second World War, underground works restarted on a larger scale with the construction of new hydropower plants in the Alps. The extension of the road and rail networks then further increased the demand for underground structures. Initially it was, in particular, the owners of hydropower plants, who were open to new developments and also invested in research. The benefits of the application of shotcrete were soon recognized; even thin layers applied onto the rock prevented disintegration, and thus practically eliminated the dominant effect of loosening associated with the traditional timber and steel supports [10].

BIRTH OF A NEW METHOD

Bolting had already been used for quite some time in mines to fix unstable blocks, but the systematic application in galleries, tunnels and caverns only started in the 1950s. Reports describing early applications can be found in [11] [12] [13]. In Austria, the first systematic application of shotcrete and bolts was in the headrace tunnel of the Prutz-Imst HPP in 1953 to 1956 [14] [15]. Measurements of rock mass displacements provided valuable insights [16]. The systematic combination of grouted bolts (Perfo) and shotcrete as the only support for larger tunnels is reported by Rabcewicz in [17].

The method not only had considerable technical, but also economical advantages. It was then Rabcewicz [1], who combined theoretical considerations and his extensive practical experience to an applicable method, and gave it the name New Austrian Tunneling Method (NATM) to distinguish it from the traditional Austrian method, which had been used particularly in poor ground conditions.

Applications in road and railway tunnels with shallow cover followed in Austria (Massenberg Tunnel) and Germany (Schwaikheim Tunnel) [18]. The importance of observing system behaviour as a means of controlling stability and optimising excavation and support were emphasised.

RAPID ADOPTION

The amazing success of the method in poor ground conditions increasingly motivated clients to use it. This was a risk to a certain extent, as no proven design methods existed at the time, and lining thicknesses were considerably less than with the traditional methods.

Milestones in the development of the method included the Tauern motorway tunnel in Austria and the large caverns of the Tarbela dam project in Pakistan (see Figure 1) [19].

In the Tauern tunnel, faulted rocks with high overburden, causing large displacements had to be dealt with. After damage occurred to the support, open gaps were left in the shotcrete lining [20]. This caused some discussion among the proponents of the method [21] [22].

The method soon spread all over the world, making tunnelling even possible in very difficult ground conditions, while at the same time considerably reducing costs. What has not always been considered is the fact that an observational approach requires organizational provisions as well as qualified engineers and miners. Another milestone in the application of the NATM the construction of parts of the Frankfurt Metro, where the method was first used in soft ground [23].

DESIGN STRATEGIES

In the beginning, design was mainly based on experience. The need for structural design methods led to the development of the so-called shear failure theory [24], which served well for several years. The ground reaction curve has also been used for

1970

Since this decade, the rapid advance of computer technology has made it possible to more realistically model ground-support interactions

a long time for explaining the basic mechanism of stress redistribution and interaction of the ground with the support [25]. Closed form solutions [26] served for the preliminary design of underground openings, and are still in use for rough estimates or to check the results of numerical simulations.

It has always been common practice in Austria to classify the ground according to its behaviour, rather than by using rating methods [27] [28]. The traditional way of classification of the behaviour in basically three major categories has been replaced by the Guideline for Geotechnical Design of Underground Structures [35], where a clear distinction is made between ground behaviour and system behaviour, listing eleven basic categories of ground behaviour.

With the rapid development of computers and software since the 1970s, it has become possible to model the ground and its interaction with excavation and support much more realistically. Continuous further development of the tools as well as the material models for ground and support have improved the modelling capability, and are turning what was previously considered as the 'art of tunnelling' into an engineering task.

Another integral part of the design is the geotechnical framework plan, which specifies which construction measures are mandatory in each section of the tunnel, and also defines the range of allowable on-site decisions. Continuous updating of the ground model and adjustment of the design, as more information becomes available during construction, is common practice, as are back-analyses.

MONITORING

The importance of monitoring has always been emphasised since the introduction of the method [29]. While initially traditional convergence measurements and levelling were carried out, absolute displacement measurement methods were introduced in the second half of the 1980s [30]. This has become standard practice on Austrian tunnel sites. Quite some effort has been put into the development of data evaluation and interpretation tools, which nowadays allow maximum use to be made of the acquired data. The evaluation of lining stresses on the basis of the measured displacements, considering the rheological behaviour of shotcrete [31], allows continuous observation of the state of the lining, and reaction over time, in case the

utilisation reaches high levels. Observing various displacement trends permits the detection of geological features outside the visible area and ahead of the face [32] [33]. It is common practice in Austria for the client to organise the monitoring and make sure that qualified personnel carry out the measurements, as well as the evaluation of the data and its interpretation.

CONTRACT SET-UP AND SITE ORGANISATION

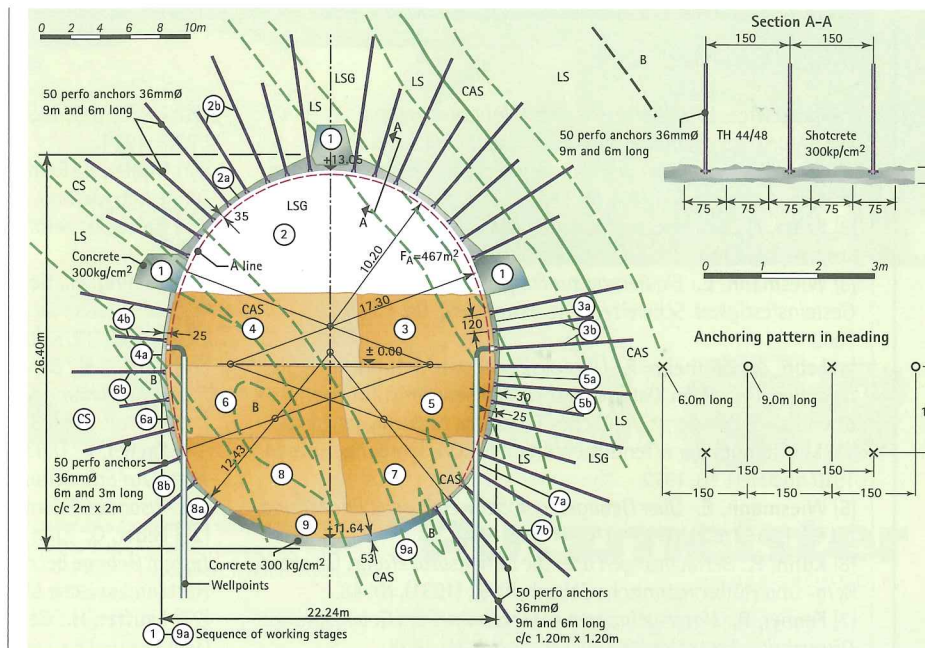
Successful tunnelling requires appropriate contractual provisions and a well-organised site to enable quick decisions. Risk sharing is a principle in Austrian tunnelling contracts, with the client assuming the geological risk, and the contractor the performance risk. Naturally this requires an intense involvement of the client during construction. For many years there has been an Austrian Standard, which sets out the basic outline of tunnelling contracts [34]. The aim of the standard, which was jointly developed by all parties and has been revised several times, is to provide fair compensation, while at the same time guaranteeing the required flexibility to adjust construction methods as required during construction. All decisions regarding excavation and support are made jointly by the contractor and the engineer.

It is common practice on sites with complex geotechnical conditions that a geotechnical engineer is appointed to take care of all geotechnical aspects as the representative of the designer on site. He is responsible for ground characterisation, short-term predictions, the monitoring programme and data evaluation and interpretation, as well as production and supervision of the geotechnical safety management plan. He issues recommendations for excavation and support and his reports are available to all parties involved.

In many cases an independent expert is engaged to assist in difficult geotechnical questions, also serving as an umpire in case of disagreement between contractor and owner.

GUIDELINES

Over the years several guidelines have been issued. One to be mentioned is the Guideline for the Geotechnical Design of Underground Structures [35]. The guideline describes a risk-oriented general procedure to be followed during design and construction, with the emphasis on a structured process. The aim is to ensure that the potential hazards and behaviours are identified



Above: Figure 1, Excavation and support of a transition at the Tarbela dam project; early 1970s [19]

during design, and the appropriate construction measures assigned in a consistent and traceable way.

Other guidelines refer to the production, application and testing of shotcrete and inner lining [36] [37]. Several working groups within the Austrian Society for Geomechanics are active in developing new handbooks and guidelines.

IMPORTANT NON-TECHNICAL FACTORS

NATM is clearly an observational approach, and as such requires constant communication and interaction between the contract parties. For successful implementation of such an approach, not only technical, but also social competence is required. This is valid not only for the management, but also for foremen and miners. Well-trained personnel at all levels are a key factor for the successful application of the method.

Another key issue is sharing of experience, as well as critical discussion. This has always been promoted in Austria, the yearly Geomechanics Colloquium with up to a thousand participants being a good example, among other conferences and workshops.

DEVELOPMENT AND INNOVATION

Development of a method is only possible when on the

"My wish would be for the industry to regard tunnelling as a regular engineering task and reduce the emotions and mysticism"

one hand there is motivation of researchers, designers and construction companies, and on the other hand clients are willing to implement innovation, even if this is associated with some risk. The need for the creation of research and teaching institutions dealing with underground engineering has been recognised, and in addition to the existing geotechnical institutes, specialised institutes have been established at the Mining University Leoben in 1974 and Graz University of Technology in 1992

By installing yielding elements into the lining right at the

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face, the capacity of the shotcrete is better used and displacements reduced.

CONCLUSION

Successful application of NATM requires competence. This competence must be available at all levels: clients, consultants, contractors, research institutions, as well as engineers, technicians, foremen, and miners. The complex nature of underground construction demands unbiased thinking, geotechnic knowledge, decision-making competence

■ *This and the other papers presented at the 2012 Geomechanics Colloquium were presented in Geomechanics and Tunneling Volume Five, Ernst & Sohn*

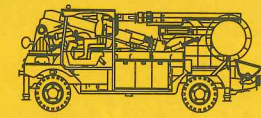
and a willingness to cooperate.

Close cooperation between all parties involved; sharing of experience; further development of investigation, design, construction, and monitoring methods; implementation of fair and flexible contract models and appropriate site organization allow the construction of high quality tunnels, even in the most complex geological conditions, at surprisingly low cost and with a minimum of disputes.

The key to success is actively adjusting the methods to the ground conditions encountered, and creating the environment in which best use can be made of the flexibility of the method. Setbacks have been observed in many cases where only single elements of the system were adopted

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BLAST PROTECTION DESIGN

The security of tunnels against potential detonated explosions from within and outside the tunnel structure is a main challenge facing to owners and operators of tunnel systems, particularly those used for vehicle or rail traffic. This paper by **Sunghoon Choi** of Parsons Brinckerhoff USA introduces a design practice recently developed for protecting underground structures from explosion in USA

THE AUTHOR has published a tunnel security design guideline in 2006 and 2012 (Choi & Munfakh, 2006 and Choi, 2012). Since that time the author has found the method to be very practical and useful and the guideline has been implemented in many tunnel security design practice. As the blast protective design was being performed, however, up to date approach and methodology have been added into the guideline. The new proposed guideline is intended to clearly explain how to assess the risk and vulnerability, how to analyse the blast impact on the structures including progressive failure potential identification, and to present the latest developed tunnel blast protection measures.

The protective design of tunnels consists of identification of the potential threats to the underground facility, evaluation of its vulnerability and risk level, analysing the impact of internal and external threats on its assets and providing internal and/or external structural hardening measures, and finally cost-benefit analysis. The guideline presented in this paper relies on credible information gathering and the use of proven methods that have been successfully applied to and accepted in the tunnel design practice in USA.

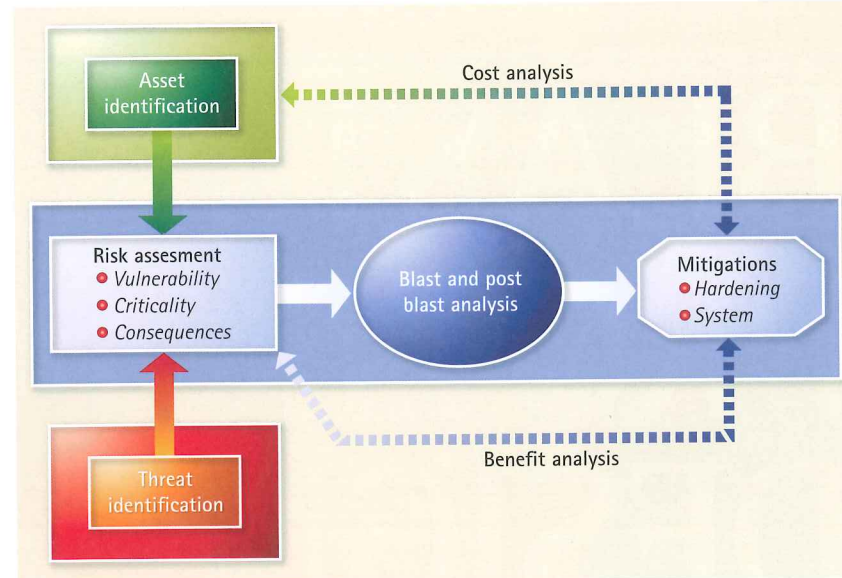
THREAT AND VULNERABILITY RISK ASSESSMENT

The proposed threat and vulnerability risk assessment includes four stages: (1) identification of project assets and threats, (2) development of threat-asset matrix, (3) risk assessment, (4) set priority. The purpose of the threat and vulnerability/risk assessment is (1) to provide safety and security guidelines to identify principal vulnerabilities of assets to various hazards and threats and (2) to provide input data to be employed for the subsequent blast analysis, expressed in terms of threat locations, design basis threats (charge weights), and tolerable tunnel damage level.

The threat profiles for the given tunnel should be compelled enough to include the requirement to elevate the security program to include special counter terrorism design measures. This is in addition to design provisions for conventional security responses for traditional crimes against persons and property, which require routine response and security management. Project site development characteristics and threat assessment considerations that affect the project profiles are then summarised. These characteristics are inherent in the project as a result of its critical transportation function, location, occupancy and connection to adjacent transportation systems. Five major categories of the intentional threats to tunnel structures are vehicle bomb threat, waterborne threat, fire threat, cyber threat, and sabotage of mechanical, electrical and communication system.

The threat-asset matrix identifies each asset and the corresponding general threat scenario that was evaluated and scored. This is accomplished by individually evaluating each asset on the basis of its location within the project, program of use, adjacent structures, occupancies and activities.

The next step is to quantify the risk



Above: The four-step risk assessment for threat and vulnerability

to the various assets as a function of three factors including criticality, vulnerability and consequences. This approach follows the same basic approach as that used in conventional risk assessment and analysis. Criticality is a measure of the importance of the asset. Criticality identifies which assets within the tunnel system are relatively more important to protect from attack. Vulnerability is a measure of how likely the asset is to be attacked successfully by a given threat. Vulnerability identifies which threats to which assets are relatively more likely to occur. Consequences are a measure of the effects if the given threat is successfully carried out against the asset. Consequences identify which threats at which assets are relatively more detrimental. For each asset-threat combination, the single measure of criticality, vulnerability and consequences is taken as the straight average of the attribute scores. Then, the risk can be calculated for the each asset-threat combination. The results of the risk calculation provide a comprehensive, systematic, and rational basis for thoroughly evaluating the risks associated with assets and deciding the most effective means for mitigating these risks. The results provide the road map for developing mitigation strategy alternatives by threat scenario and asset. The risk score enables to prioritise the strengthening of assets and further blast protective design and construction.

BLAST AND POST BLAST ANALYSIS

Prediction of material damage under a dynamic loading is a complex function of several factors such as loading magnitude, loading rate and loading duration. If the material experiences the same magnitude of loading at a different loading rate, the response will be different. The current paper introduces a blast analysis method, which fully incorporates dynamic properties of materials as well as strain rate effects, so that a dynamic structural response could be predicted reliably when the structure was subjected to a blast loading.

Blast Analysis

The purpose of the blast analysis is assessment of the structural damage due to threat scenarios and development of economical and simple-to-construct strengthening measure. The first task is to assess and identify the most vulnerable locations along the tunnel alignment and across the cross section. The most vulnerable locations are selected based on tunnel structural integrity, tunnel alignment, tunnel depth,

5
the number of major categories of threats to tunnel structures

2006
Year the author's initial guideline for tunnel security design had been published



Above: Firefighter at work

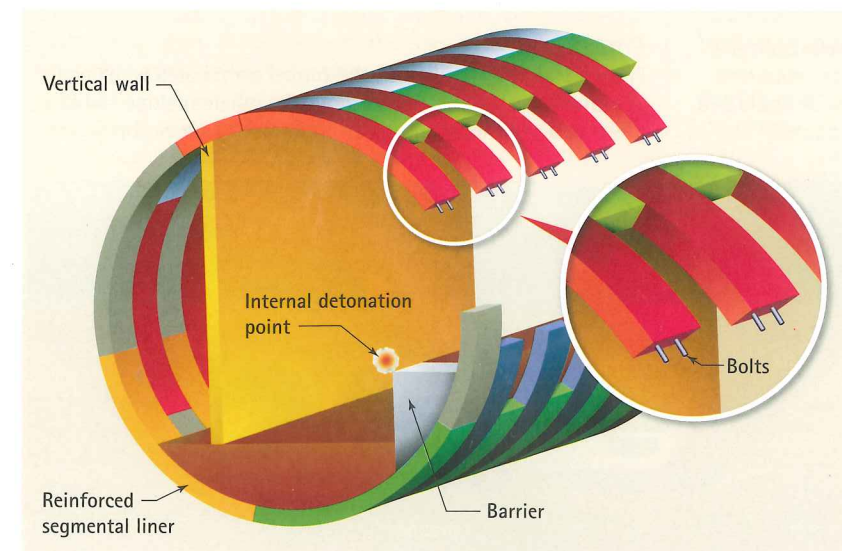
surrounding ground condition and consequences, i.e. potential of progressive failure or collapse of adjacent underground and surface structures. The second task is to develop three-dimensional finite element models based on the provided plans that capture and characterise the behavior of blast pressure propagation and the dynamic interaction of blast pressure and structures. Modelling of all structural components including, but not limited to, tunnel structures, adjacent columns, surrounding ground and adjacent building structures, shall be in accordance with accepted practice for similar type analyses used to identify and assess potential modes of failure and damage levels. The third task is to perform three-dimensional nonlinear, coupled Euler-Lagrange blast analyses to identify

Below: Developing 3D models help identify damage

the extent of damage under the postulated blast threat scenarios and selected detonation points. Of particular concern is damage assessment to tunnel structures and progressive type failure or collapse of the tunnel structures and adjacent underground and surface structures including buildings. Finally, the fourth task is to develop strengthening measures and to conduct blast analysis to verify effectiveness of the measures. A simple cost-benefit analysis will be conducted to select the most economical, easy-to-construct strengthening measure for the project.

Bored/Mined Tunnels

In cases where a tunnel is located in significant depth or overlying structures exist above the tunnel alignment, bored or mined underground tunnel construction is typically the preferred. The bored tunnel structures are usually composed of concrete. Even though the ballast fill concrete and concrete walk benches provide some cushion against an interior blast, due to the brittle nature of concrete materials, the bored tunnel is likely to be very vulnerable to an interior blast as well as an external blast set from the shipping channel bed. When the tunnels are underneath the water body, cracking or failure of the concrete liner may allow inundation with



water and resulting in high flooding potential in the transportation system if the tunnel is connected to underground transportation network. When the ground stability is not preserved, a failure of tunnel liner would impact adjacent surface and underground structures. When segmented precast concrete lining is used, the behavior of the lining is also of concern. Three dimensional blast analysis enables to model behavior of bolted segment to investigate the performance of the segments when they are subjected to internal blast loads and to recommend a proper dimension and number of bolts to be used.

Cut and cover Tunnels

Shallow depth tunnels in land are frequently designed using the cut and cover method. This technique involves braced, trench-type excavation and placement of fill materials over the finished structure. The excavation is typically rectangular in cross section in relatively shallow depth. It is likely that the cut and cover sections of the tunnels will be extremely vulnerable to an interior blast due to less confinement from surrounding ground. However, it is probable that the cut and cover sections will be less vulnerable to a surface blast due to the open-air nature of the blast and soil cover over the tunnel. For U-tunnel section, where the tunnel structure is open and not covered, the vulnerability will be extremely high due to relatively easy delivery method of explosives.

Immersed Tube

Immersed tube tunnels are employed to traverse a body of water. The tunnel construction method involves (1) construction of tunnel sections in an offsite casting or fabrication facility that are finished with bulkheads and transported to the tunnel site; (2) placement of the sections in a pre-excavated trench, jointing and connecting together and ballasting/anchoring; and (3) removal of temporary bulkheads and backfilling the excavation. The top of the tunnel should be at least 5ft (1.5m) below the original bottom to allow for an adequate protective backfill. The typical immersed tubes consist of concrete liner, steel shell and concrete tube. The concrete liner and concrete tubes are load bearing elements, while the steel shell is usually not considered to be a load bearing element but rather acts as a waterproofing membrane. The joints between segments may be the most vulnerable if it is not covered with

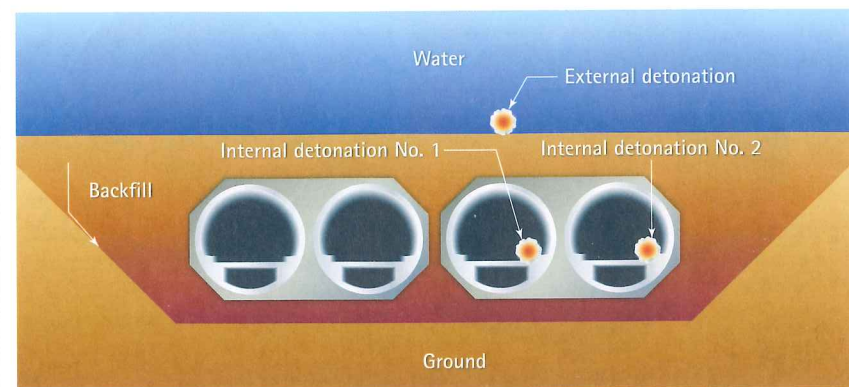
1.5

Meters at minimum the top of an immersed tunnel should be below the original bottom

5

Per cent of hundreds of recorded terrorist attacks that targeted infrastructure in the last 50 years

Below: Example of an immersed tunnel, liners and its backfill



tremie concrete. Local breach of the main tunnel structures would induce complete inundation with water and cause flooding in the underground transportation system. Flooding may also introduce large quantities of sand, silt, gravel or shear zone debris. Significant lengths of tunnel can become filled with debris or backfill in a short period of time. For this reason, the immersed tube structures are considered to be the most vulnerable elements.

Underground Stations

The underground stations are constructed by either cut-and-cover method or bored/mined. Considering high level of access, exposed population and consequences, the station structures are likely to be very vulnerable to an interior blast. For the underground stations, hand-carried satchel bombs and suitcase bombs are the predominant mode of explosive attack, while subway storage yards, service facilities, and the shipping channels above the tunnels allow for the potential delivery of much larger explosive/incendiary materials.

Ventilation Shafts

Ventilation shafts are typically reinforced concrete shafts extended from the land surface. At the interface of the shafts and the bored tunnel, they may be more vulnerable to damage because high stress concentrations may occur at these junctions. However, due to access restrictions, only a small amount of explosive is likely to be brought into the shafts, therefore an interior threat within the emergency exit shafts is not considered critical. A more critical threat would be one introduced to the external detonation that large amount of explosives are carried by vehicle.

Cross Passageways

The cross passageways may be vulnerable to damage because high stress concentrations may occur at the junctions with main tunnels and given the same amount of explosive charge, the resulting blast peak pressure in a cross passageway tunnel may be greater than that in the main tunnel due to its smaller cross-sectional geometry. However, from an operational standpoint, the cross passageways are not considered to be more critical than the main tunnel elements because of their greater degree of redundancy due to a number of cross passageways. Furthermore, local failure or collapse of one or more of the cross passageway tunnels may not necessarily affect the stability of the main tunnels or prevent their continuous use if the water inflow is controlled.

Portal

From a stability standpoint, the tunnel portal area is generally one of the critical locations due to the inherent slope stability problem and/or retaining structure failure. Tunnel portals are

Questions from the floor

David Gullick, Parsons Brinckerhoff asked how the size of charge was decided.

Choi responded that sizes are usually decided by security personnel who establish threat scenarios where methodologies as to how certain charges can be applied to the structure are developed and charge size comes out of this. The actual size of charge used is classified but it is usually in the order of something that can be carried by a Transit sized van. Backpack sized charges are also used in the modelling.

Guy Lance, consultant asked about the statistics used in the presentation, and were they based on worldwide data or just USA. Also what was the chosen definition of a terrorist.

Choi said worldwide statistics have been shown. The definition is out of the presenter's knowledge and control. PB usually works closely with security personnel and specialists working for the authorities. PB's own security advisors are usually retired US Navy or US Army and these people define the terrorist and this is developed into an input for the models.

Lance asked if it be true to say that Choi defines the solution and not the problem.

Choi confirms.

Myles O'Reilly, retired asked what the actual number of incidences where infrastructure has been damaged by terrorism is. He adds that the presentation only refers to percentages.

Choi said statistics in the presentation show that of the several hundred recorded terrorist attacks about 5 per cent have been targeted on infrastructure over the last 50 or so years.

Andrew Smith, Joseph Gallagher said the presentation had been concerned about the design for explosion, but there is also a need to design against a catastrophic fire. He asked if the design for one compromise the design for the other.

Choi said the design loads for each are very different. We are looking for a design that can cope with fire, explosion and also earthquake loads. Blast loads occur over a few milliseconds, while earthquake loads occur over a longer timeframe, but the design for one can assist in the design of the other. In the past design has been done separately for each item by separate specialists resulting in very thick lining designs. In the future they are working towards merging each extreme load into a single solution and research is currently being undertaken to find a material resistant to all three design cases.

Steve Psomas, Morgan Sindall asked how the level of damage is assessed for DUCON (ductile concrete) and if the model was based on strain criteria.

Choi responded that the models are validated using explosion tests on materials to assess actual damage from a given charge on the modelled material. The models are based on strain as this works better than stress although this leads to lengthy analysis times, often in excess of 24 hours.

Neville Harrison, consultant pointed out that there is experience

where an accident in a cast iron lined tunnel caused a blast pressure of 9 bars and no damage to the lining was sustained.

Choi said that this was a small blast load. A backpack sized charge could give rise to a pressure 20 times greater than this and it is possible local damage to cast iron linings will occur depending on where the charges are positioned in relation to the lining. The examples presented look more at charges carried in a van and issues related to road tunnels where such charges could be transported into position where damage would be greater.

Will Wholey, TPS Consult asked how the model that considered a blast on the seabed above the tunnel was validated.

Choi said blast loads to concrete, steel and ground are well defined and are consistent with the crater sizes established in field tests. Blast waves through ground were studied in Newmark's paper in 1963 and this is applied in the model and has been independently verified. Blast waves through water and their impacts are different than in ground and various research facilities work to validate data produced by the models.

P. Linkeshwaren, ESL questioned the cost benefit analysis where a statement was made that DUCON was very expensive but it appeared to be similar in cost to other measures.

Choi clarified that DUCON is expensive when compared to conventional concrete but is similar in cost to alternative blast protection measures.

Panos Spiridis, Dr Sauer asked how ground parameters are taken into account in the analysis.

Choi said his paper discusses ground conditions in detail. If the ground provides good confinement then the tunnel will perform better. A blast load is instantaneous not a permanent load condition as per the ground so the focus is on the structure rather than the ground.

Spiridis queried if the ground has a dampening effect.

Choi said seismic models are considered for the ground in the model. The model considers this separately to the structure and PB are currently researching the effect that differing grounds have on the blast model.

Spiridis asked if the designers have responsibility for other structures.

Choi responded that, yes, this is done during the post blast analysis where progressive collapse analysis is carried out and an entire model can comprise structures external to analysed tunnel.

Gordon Cook, fire consultant asked which organisation carries out research work in the US.

Choi said the US Army/Navy conduct tests which are shared with PB. Authorities require that the owner funds three tests for new projects and this improves the models. The US Force's tests are to research destroying tunnels effectively and this research needs to be developed to protect tunnels. Research is made available and this is always used to validate the model.

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therefore considered to be particularly vulnerable during extreme events. Nevertheless, the consequences of a portal failure are generally considered to be less severe than those of main tunnel element failures because the repair can be done in an open space. The flooding is not an issue when a portal is damaged or collapses, so the repair time and associated costs are relatively low compared to the other parts of the tunnel. Furthermore, at the portal, the blast is less confined and the energy dissipates away rapidly than it will in the confined tunnel environment.

POST BLAST ANALYSIS: PROGRESSIVE COLLAPSE AND FLOOD POTENTIAL

In addition to the evaluation of damage extents caused by the blast-induced loading, post-blast behavior should be analysed to evaluate progressive type failure/collapse where continued failure may occur due to the structural weakening, load redistribution, excessive displacements, water inflow or running ground into the tunnel.

Progressive collapse of underground structures is of great concern, even if the underground structural elements are not completely damaged during the blast. They may be weakened or softened, at which point the normal loading imparted during operations would cause further damage or failure to the structures. The progressive failure analyses consider the structure in operation, subsequent to the blast loading. The post blast progressive collapse analysis is performed in such a way, where the damaged area(s) are

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removed and by applying load combinations to the structures. The segmental lined tunnel is loaded by surrounding ground and water pressure. The complex underground station is assumed to be fully loaded with trains on each track level, with the mezzanine level and platforms assumed to be fully occupied with the full live load and dead load expected.

The stability of the ground is also of concern with the breach failure of the liner when the stability of surrounding ground is not preserved. For soft ground tunnels under water, ground failure and subsequent flowing condition into the tunnel associated with the breached concrete liner failure is a more likely scenario. This ground failure and/or flowing condition may result in large water inflow because of the high water pressure and infinite water supply.

DAMAGE LEVEL

The damage levels for each blast analysis are assigned after evaluating the damaged area, determining the remedial construction activities that would be required to return the tunnel to its normal operating condition. Consequences including flooding potential, ground stability, and progressive failure or collapse are also considered in the designation of damage level. In the protective design or strengthening of tunnel structures, it is reasonable to accept a moderate level of damage to the tunnel elements such that disruptions to operations would be limited to a short period of time. Such a level of damage acceptance may result in greater affordability of the tunnel construction cost.

BLAST PROTECTION MEASURES

During a blast loading, the structures make an attempt to balance the kinetic energy from the blast with the strain energy of the structural members. If the kinetic energy from the blast is greater than the total strain energy of a structural member, the structural member will be breached. The total strain energy is a function of the area under the stress-strain curve of a material used to make up that structural member. Thus, ductile materials can absorb more blast energy. Various products have been proposed in the market for blast protection of the structures. The most common products used in the protective design are summarised (Choi 2012).

COST BENEFIT ANALYSIS

The last stage of the blast protective design is the cost-benefit analysis. The cost-benefit analysis is a systematic approach to the problem of choosing the best method of allocating scarce resources to achieve a given objective. The cost-benefit analysis includes four stages; (1) defining an objective or need, (2) identifying blast protection measures, (3) estimating the costs and benefits of each blast protection measures, and (4) recommending a preferred solution.

CONCLUSIONS

Tunnel safety and security require the systematic application of engineering, technology, and management tools to identify, analyze, and control hazards and vulnerabilities within operational, budget and time constraints. This security can be enhanced through a comprehensive process ranging from vulnerability assessment to implementation of remedial measures. They encompass all of the integral factors that comprise a tunnel, including people, operating procedures, systems and controls and the physical aspects of the tunnel components

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www.tunnel.or.kr

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12-14 March 2013
Moscow, Russia
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www.intertunnelrussia.com

Bauma Munich

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The 12th International Conference "Underground Construction Prague 2013"

22-24 April 2013
Prague, Czech Republic
The ITA-AITES Czech Tunelling Association under the auspices of the ITA-AITES International Tunelling and Underground Space Association is organising UC 2013. The Czech Republic is implementing and preparing significant underground structures.
www.ita-aites.cz/en/conference_underg_constr/conference-uc-2013/

Tunnel Expo China

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Shanghai, China
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<http://www.chinaexhibition.com>

World Tunnel Congress

31 May - 7 June 2013
Geneva, Switzerland
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wtc2013.ch

Construction Expo

5-8 June 2013
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www.constructionexpo.com.br

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Organised by the Norwegian Public Roads Administration, the focus is on extreme crossings and new technology.
www.sc2013.no

RETC

23-26 June 2013
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www.retc.org

ISARC/WMC 2013

11-15 August 2013
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<http://www.isarc2013.org>
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2-6 September 2013
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www.issmge2013.org

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www.bauma-africa.com

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www.stuva.de/en

World Tunnel Congress

9-15 May 2014
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www.wtc2014.com.br

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BTS / MinSouth joint event - Details to be confirmed

21 February 2013
Details yet to be announced.

Details for future 2013 BTS meetings are yet to be confirmed. Please check www.britishtunnelling.org.uk for updated information.

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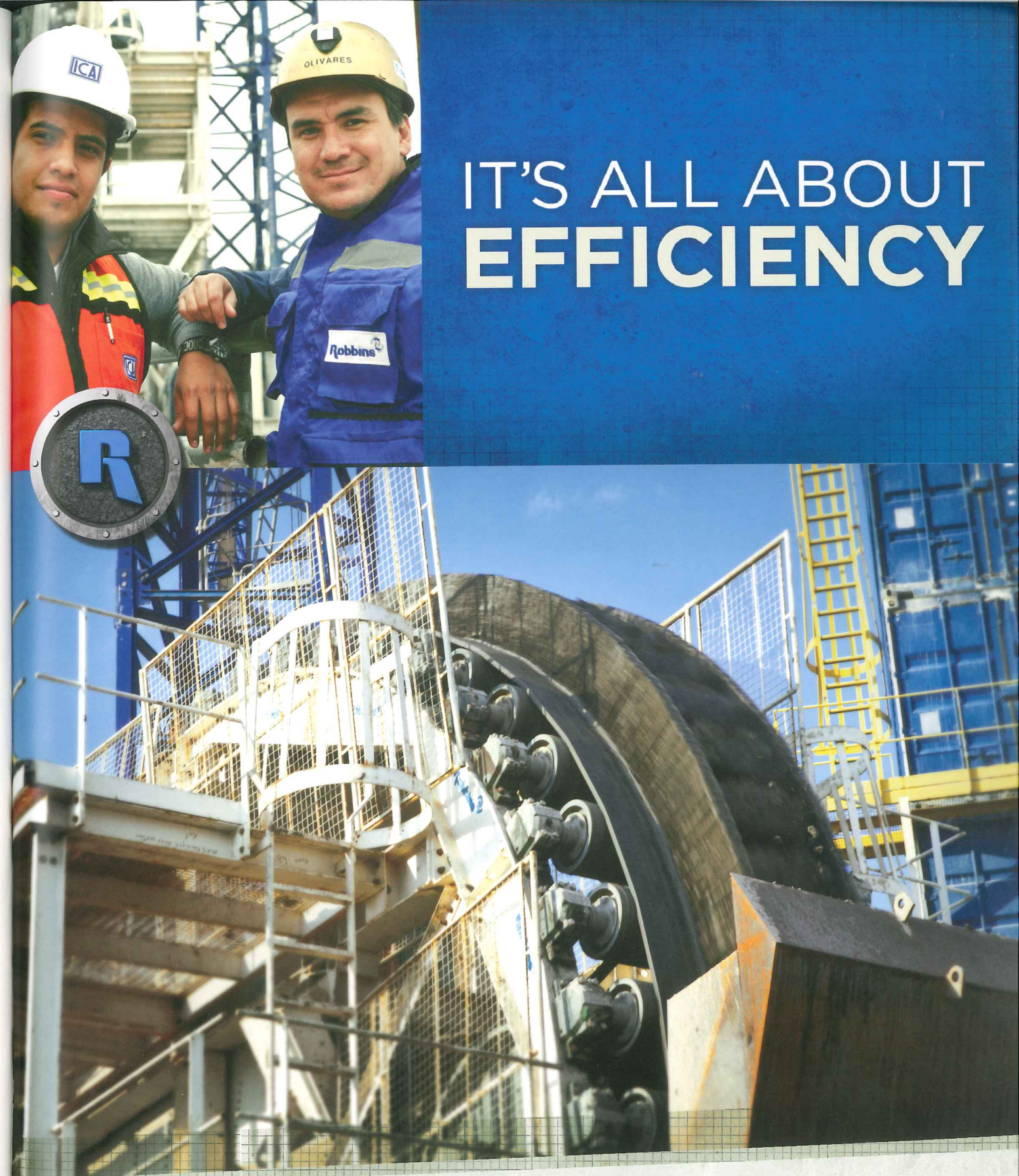
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