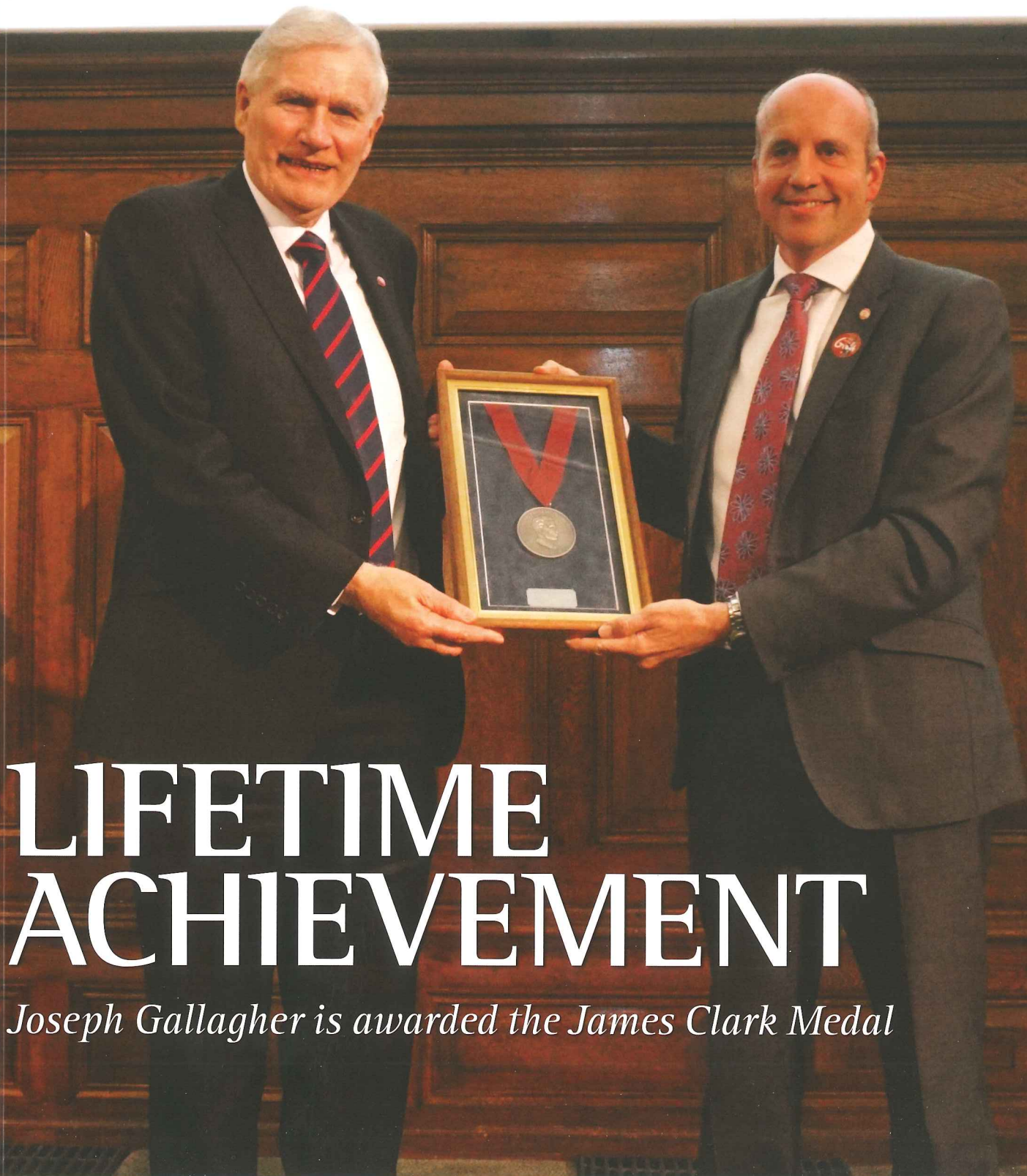


INTERNATIONAL EDITION

September 2017

Tunnels

AND TUNNELLING



LIFETIME ACHIEVEMENT

Joseph Gallagher is awarded the James Clark Medal

Contractors:
 › Arge Tulfes Pfons
 › Strabag AG
 › Salini Impregilo S.p.A.

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THE NUCLEAR SOLUTION

Balfour Beatty has announced that it is EDF Energy's preferred bidder for the Hinkley Point C nuclear power station tunnelling and marine works package. The four-year contract will involve the construction of three tunnels for a total of 9.5km in length and 7m in diameter. The tunnels will form part of the cooling system required.

Hinkley Point C is the first of the new generation of nuclear power plants to be built in the UK, and the first to be constructed for more than 20 years. As always, nuclear power comes under fire from all corners. Even the National Audit Office has argued that costs and risks have not fully mapped out in a report published this year.

The project is estimated to cost GBP 18bn to construct and should meet 7% of Great Britain's power requirements in the mid-2020s. The cost will be met entirely by France's EDF and China's CGN, which will then exact GBP 92.50 (in 2012 prices) per MWh of electricity generated.

This 'strike price' has been the source of much of the criticism, which is approximately double the current wholesale rates. The auditors have noted that this was due to a lack of competition, but stated clearly that the government has committed consumers and taxpayers to a high cost and risky deal.

The problem with a strike price is that if prices dip below the agreed sum, the country is committed to topping up to that level (until 2035 in this case).

Alex Conacher

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



Although if prices soar above it, the plant owners would suffer.

However, nuclear needs to happen. Solar is looking like the runaway victor in the renewable sector and we can expect exciting things from that industry, but with the numerous energy storage options still woeful (although the comparatively primitive option of pumped storage, which requires tunnelling, leads the pack in terms of energy retention), the only effective way to guarantee base load power levels during weaker generating hours, while still being low-carbon, is nuclear.

Besides the fact that a substantial portion of existing capacity is fast approaching the end of its working life, new electricity demands may provide a sudden shock to the system sooner rather than later. The expected rise of the electric car in particular will transfer an enormous amount of energy demand from petroleum to electricity, and society needs to be ready.

Nuclear and/or storage is the future for much of our energy production. Fortunately for the industry, both (currently) require tunnelling. Unfortunately for the country, one seems to be expensive and the other technologically challenging.

This month...

20 YEARS AGO

Delayed closure of the invert is believed to be the principal factor that caused an NATM tunnel collapse on the Sao Paulo Metro at 10:15pm on 15 July. The collapse took with it a private house but there were no fatalities or serious injuries, although the residents of several houses were evacuated. According to client engineers, the first signs of tunnel distress were evident early in the morning when cracks appeared in the shotcrete. These expanded as talks about how to stabilise the situation continued throughout the day. At 8pm the tunnelling crews accepted that collapse was imminent and raised the alarm. The tunnel is some 14m below the surface, along the Green Line extension.

Tunnels and Tunnelling, September 1997, page 7

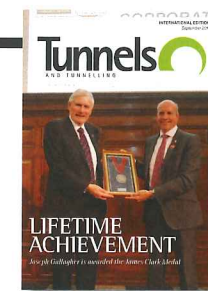
30 YEARS AGO

All legislation for the existence of a fixed tunnel link between Britain and France is now passed and the developers are free to embark on the intense construction schedule which is expected to have the link operating by May 1993. The French approved the scheme in April and June 1987 and in the last weeks of July, the Queen granted Royal Assent. Margaret Thatcher and Francois Mitterand then signed the necessary international treaty. This now clears the way for the launch of the third equity tranche, an international public share issue provisionally scheduled for November 1987.

Tunnels and Tunnelling, September 1987, page 9

Cover

The front cover shows Joseph Gallagher (left) receiving the James Clark Medal from the BTS chair.



Next issue

In the next issue of *Tunnels and Tunnelling International* we have the winning Harding Prize paper written by Omar Mohammed of TfL, a look at the new ACI guidelines, an article on the total cost of TBM ownership and the Xe-Pian Xe-Namnoy project.

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AHEAD OF THE CURVE

TERRATEC Tight Radius Shield (TRS) Earth Pressure Balance TBMs are currently proving their metal on a number of major utility tunnel contracts in Bangkok, Thailand.

Designed with an extreme X-type articulation system that can accommodate minimum radius curves of just 30m, these TERRATEC machines are enabling contractors to negotiate the strictest of tunnel alignment constraints, while delivering the company's trademark reliability and accuracy.

TUNNELLING SOLUTIONS | UTILITIES



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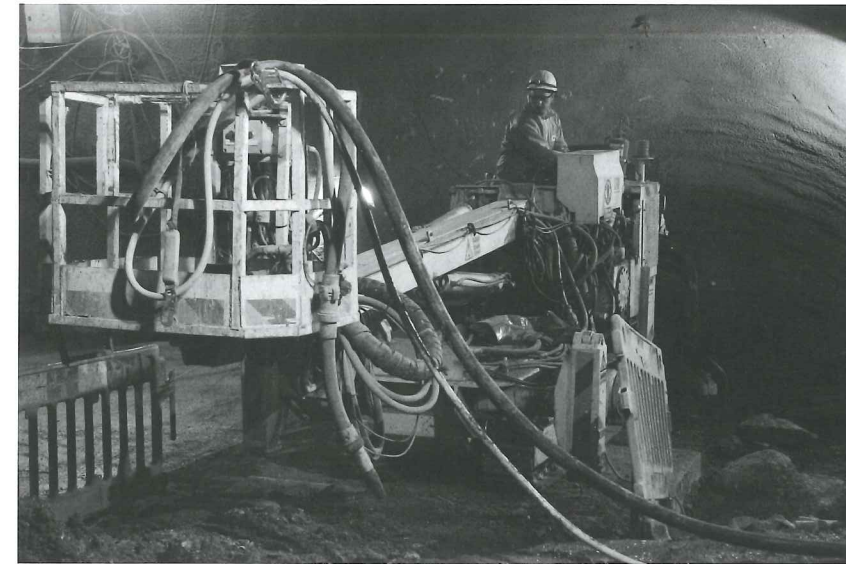
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CONSTRUCTING A SUSTAINABLE FUTURE

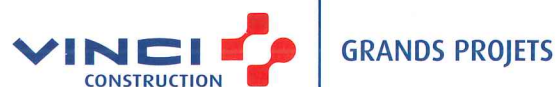
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FINAL EMSCHER BREAKTHROUGH

GERMANY — Tunnelling and pipe jacking has concluded on the Emscher sewer. The final drives, two 10km-long main collectors in the town of Oberhausen, were carried out by contractor Porr between October 2014 and June using two Herrenknecht 3,397mm diameter EPBMs.

A spokesperson for the manufacturer said: "The two EPB Shields were the only machines in the entire project using the segmental lining method. With an inside diameter of 2.6m, the twin tubes are among the smallest segmentally

lined tunnels in the world. The entire tunnelling system with a length of around 85m was designed to be accordingly compact. The logistics were also adapted for the small diameter.

"Thus, for example, a muck removal concept with a locomotive was used, where excavated material was transported in buckets to the shaft and the finished segments were transported to the tunnel face."

In terms of challenges, the alignment called for curves of 200m in radius and was situated mostly between

the A2 motorway and other inner city infrastructure. There was also a 300m-long fault zone with sandy and groundwater-bearing subsoil. Generally the geology was Emscher marl.

The Emscher is a small river that passes through a series of German cities on its way to the Rhine River. Since industrialisation in the mid-1800s, the river was used as an open channel for sewage, flood and rainwater. It reportedly became the dirtiest river in Europe. The commissioning of the 51km Emscher sewer system in 2020 will remedy this.



On 12 June the two Herrenknecht EPBMs broke through the target wall at the Oberhausen pumping station precisely on line and level

Jacobs Engineering to buy CH2M

INTERNATIONAL — Jacobs and CH2M have entered into an agreement that will see Jacobs acquire all outstanding CH2M shares for a total value of USD 3.27bn. This amount includes around USD 416M in CH2M debt.

In a statement on the benefits of the move, Jacobs Engineering hailed CH2M as the leading water design firm in the world as well as having a "preeminent brand for programme and project delivery in environmental remediation in the nuclear industry". Tunnelling was not mentioned specifically in

either case and the remainder of the statement discussed the financial benefits at length.

"We are delighted about the prospects of combining CH2M with Jacobs," said CH2M chairman and CEO Jacqueline Hinman.

"Since late in the year 2014, we've been transparent about our plans to pursue an ownership transition, providing sustained access to capital for growth. This was the unanimous choice of our Board, and the value Jacobs will provide to our stockholders, reflects genuine appreciation for our employees and the world-class work we deliver to our clients."

TUNNELS AND TUNNELLING PROJECT LISTINGS 2017

The *Tunnels and Tunnelling Annual Listings* is introducing an improved format for 2017.

This year in addition to the usual corporate details and contacts, companies will have the opportunity to list sample projects that they have participated in and showcase their expertise and innovation in a practical way.

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

Please use the link below to navigate to our website where you should be able to access a Google Form to fill out an entry for your company.

We will be accepting submissions to the *Tunnels and Tunnelling Project Listings* up to and including 1 November, but no later.

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

Brethel joins Cowi

USA — Cowi North America announced that Michael Brethel joined Cowi Tunnel as chief project manager, effective 1 August.

The company said Brethel brings more than 16 years of project management and design experience in geotechnical, structural, and tunnel engineering. "He has a highly valued combination of expertise, which has been utilized on a wide range of heavy civil projects, tunnel projects and in support of excavation designs for Washington Metropolitan Area Transit Authority, New York City Transit, New Jersey Department of Transportation, and Loudoun Water."

Prior to joining Cowi, he was a senior engineer at Lachel & Associates, Inc.

"We are very pleased that Michael has joined the COWI team. His experience will deepen our bench strength in geotechnical, structural and tunnel engineering for underground projects," says Steven Kramer, senior vice president of Cowi Tunnel North America.

Brethel will be based in Cowi's Florham Park, New Jersey, office.

Omaha CSO project celebrates TBM breakthrough

USA — The South Interceptor Force Main tunnel project in Omaha made its final breakthrough on 5 August, following a year-long delay due to a stuck TBM in unexpected ground.

City of Omaha Public Works awarded a USD 21.5M contract to Super Excavators for the South Interceptor Force Main Project - North Segment and North Gravity Sewer in September 2014, and the contractor launched a 102-inch-diameter Lovat TBM the following September.

During the 3,500ft (1km) drive, the TBM designed for rock got stuck last year, Scott Aurit, project manager at HDR told local media at the breakthrough, when the machine encountered boulders and groundwater conditions.

The approximately 70ft- (21m-) deep tunnel was mined in a limestone shale mix. The contractor excavated a rescue shaft to remove the stuck machine and launched another machine in the opposite direction in order to complete the remaining 900ft (274.32m) of the sewer tunnel drive.

Albany Park project marks blasting milestone

USA — Blasting operations for the intake shaft on a Chicago tunnel project are now complete, the Chicago Department of Transportation (CDOT) announced on 7 August. Part of the Albany Park Stormwater Diversion Tunnel project, the intake shaft is one of two 150ft- (45.7m-) deep shafts connected by a 5,700ft- (1737.36m-) long, 18ft- (5.5m-) diameter tunnel. Blasting at the outflow shaft was completed in March. The tunnel will convey excess storm water to the North Shore Channel, which has a greater capacity to hold overflow than the North Branch of the Chicago River.

"We're pleased that the blasting has been completed and the project is moving ahead on schedule," said CDOT commissioner, Rebekah Scheinfeld. "The tunnel underneath Foster Avenue is more than halfway complete and we're starting to work on the channel that will allow overflow from the North Branch to flow into the intake shaft."

Albany Park has

experienced two major floods since 2008 that have affected hundreds of homes in the northwest side community along the North Branch of the Chicago River. After the last round of flooding in April 2013, mayor Rahm Emanuel directed CDOT and the Metropolitan Water and Reclamation District (MWRD) to move forward with design and engineering of a stormwater diversion tunnel that would alleviate the threat of catastrophic flooding. The completed tunnel will have the capacity to divert 2,300 cubic feet (65 cubic meter) of water per second.

The stormwater diversion tunnel concept is developed and designed by MWH. WSP is the construction manager for the project.

CDOT awarded a USD 63M contract to Kenny Construction in 2016, which launched a contractor-owned refurbished TBM at the outflow shaft earlier this year. The TBM was rebuilt by Kenny Construction with size modifications that were designed by Robbins, and is expected to finish its drive through mostly limestone later this year. Project completion is on schedule for May 2018.

BROCKVILLE TUNNEL REOPENS IN ONTARIO

CANADA — Canada's first rail tunnel, in Brockville, Ontario, reopened on 12 August, following restoration work converting it to a recreational space connected to the city's trail system.

At 525m long, the tunnel will feature a smooth concrete travel surface and state-of-the-art energy efficient LED lighting. A programmable light show will highlight the tunnel's engineering, architectural, and geological features.

Rehabilitation work started in 2016 to update the facilities and repair and stabilize brick work.

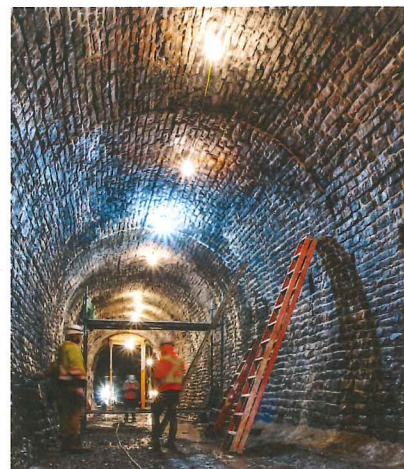
Original tunnel construction started in 1854 and, with some delays due to financial concerns, finished six years later. According to a local committee overseeing the rehabilitation project crews used three different tunnelling methods

including trenching and blasting through rock. Train operations in the tunnel ended in 1969.

The City of Brockville purchased the tunnel for CAD 1 and has done extensive work on the tunnel portals. Decades of water ingress in the closed tunnel created mineral deposits along much of the tunnel's walls.

Other tunnel features include a state-of-the-art sound system; safety, security and fire protection systems; rest areas and benches; a ventilation system; wayfinding and education signage; and public wi-fi access.

A rubber-tired tour train will take visitors back and forth, through a nearby gorge and the tunnel, to local parks and other waterfront and downtown attractions.



Canada's first rail tunnel reopened in August following restoration
 ©KEITH HARE



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Hobas and Flowtite merger approved

AUSTRIA — August saw the European Commission approve the merger of Hobas and Flowtite. The companies, owned by Amiantit and Wietersdorfer respectively, are pipe manufacturers.

Amiantit of Saudi Arabia will own and Austria's Wietersdorfer will own the new business on a 50-50 basis. The holding company will be based in Austria from September.

The European Commission stated that the proposed acquisition would raise no competition concerns

because the merged entity will continue competing with other GRP pipes manufacturers, as well as manufacturers of pipes of other materials that are used for the same applications.

John Holland names COO

AUSTRALIA — John Holland has appointed Rod Heale as its new chief operating officer (COO), a new position at the company. Heale is due to join from CPB in September. CEO Joe Barr said the appointment comes off the back of recent changes to the John Holland executive team, reflecting

a new strategic approach to grow the business and establish "an integrated offering across infrastructure and property".

Barr added: "It has been a phenomenal period for John Holland. We're on track to double the business, with a host of mega- project wins this year worth around AUD 15.5bn [USD 12.2bn]. On a number of these projects, including the Melbourne Metro Tunnel, we've shown the value of our integrated offering, with a stake in equity, design and construction, development and maintenance.

"[Heale] will join the

business to oversee John Holland's project wins and delivery. He will look after operations, working closely with the respective EGMs and their leadership teams to drive excellence and innovation.

"[Heale] is an experienced senior executive leader with more than 30 years' experience in the construction industry. He has a strong track record in transformational leadership, strategic business development and building high-performing teams. He also has extensive experience in the delivery of large and complex infrastructure and building projects across Australia and Asia."

FUGRO BAGS GEOTECHNICAL CONTRACTS AT YORK POTASH

GREAT BRITAIN — Fugro has been awarded two contracts for geotechnical and geophysical investigations at the York Potash project. The project is to develop the world's largest known high grade polyhalite deposit.

Construction includes a new mine to extract the ore, a 37km tunnel hosting an underground mineral transportation system (MTS), a granulation facility in Teesside, and an export quay on the River Tees.

The first contract requires seven deep boreholes in shaft and tunnel locations at the new mine, for strength testing of the rock formation. Drilling will be carried out to depths of 420m.

Under the second contract, Fugro is carrying out an 11-month programme of seismic investigations and wireline logging, which will be fully integrated with the geotechnical work to maximise both data yield and quality.

The combined programme will allow a detailed assessment of geological conditions to 500m depth ahead of TBM operations along the MTS alignment.

A spokesperson for Fugro said, "Geophysical and drilling investigation, laboratory testing and geoconsultancy are being combined to create a detailed geological model. This will help reduce uncertainty in the subsurface in order to manage risks associated with planning, design and construction."

Rod Eddies, Fugro's geophysical lead on the project, said: "Supporting Sirius

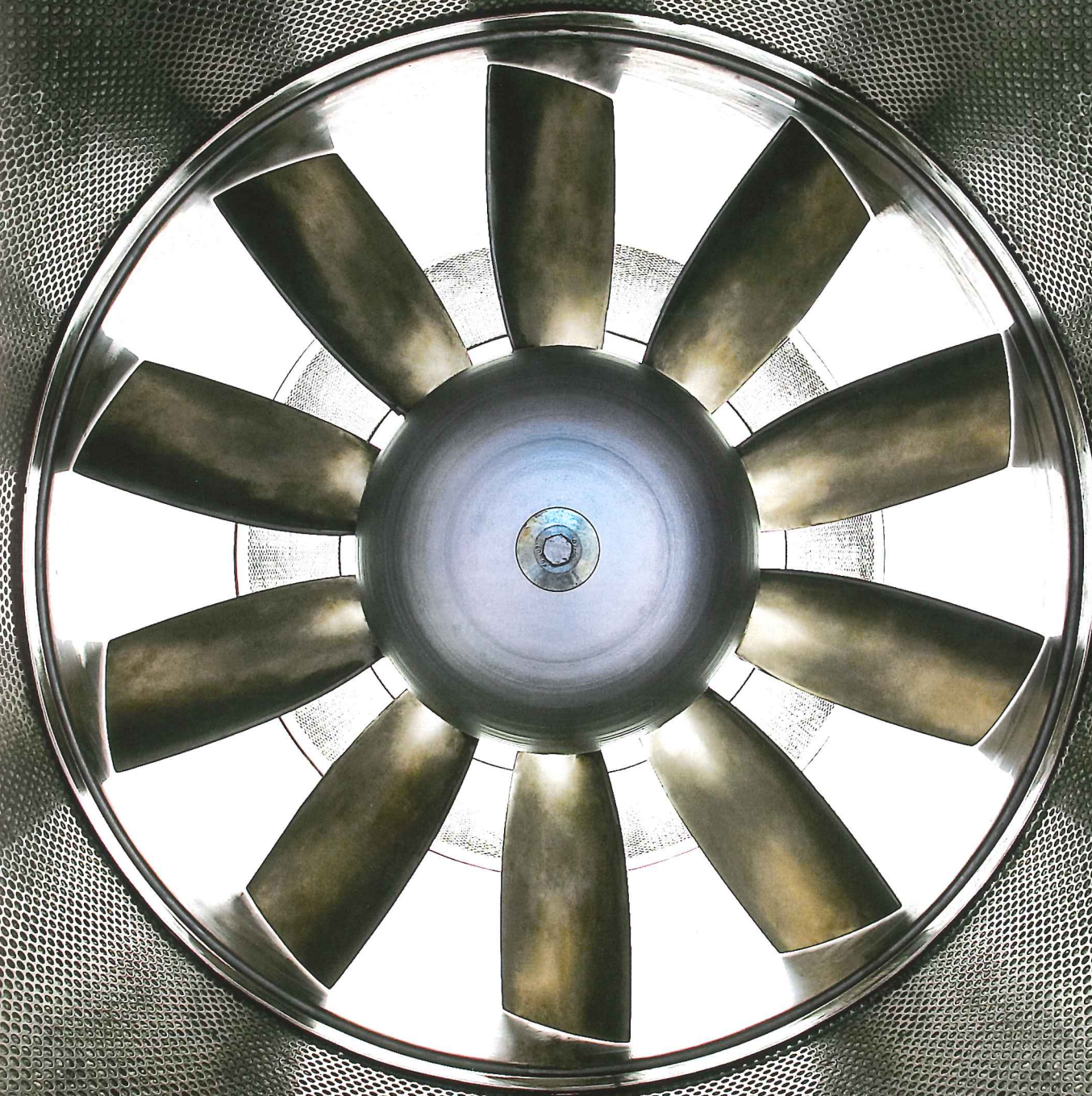
Minerals' project, which includes the UK's longest tunnel scheme, presents an exciting challenge. The information we are obtaining will provide Sirius with a more complete ground model along the tunnel alignment and will help in the design and planning of the tunnel boring machine operations."

The two contracts are already underway, with drilling and sampling expected to continue to the end of the

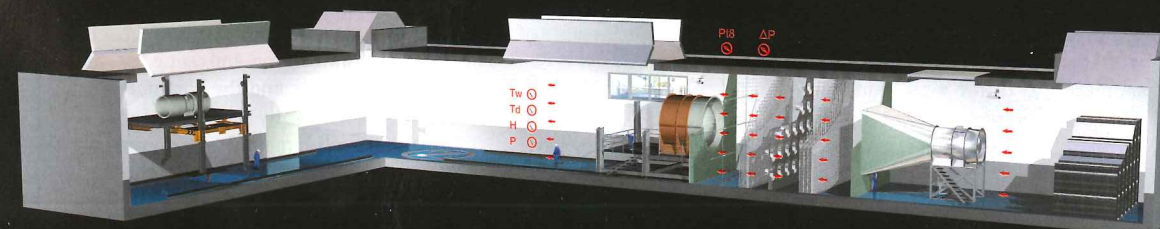
year and geophysical activities to May 2018. Fugro previously completed a series of geotechnical investigations across the project under three contract awards between 2013 and 2016. These have included preliminary geotechnical and hydrological investigations at the mine site, seven deep boreholes along the transport corridor and at the export dock, and a challenging deep inclined hole for fault characterisation.



Sirius Minerals is calling on Fugro's integrated SI capabilities for its UK polyhalite project



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ITA AWARDS SHORTLIST

INTERNATIONAL — The International Tunnelling Association (ITA) announced its shortlist for the annual awards.

A panel of 17 judges, led by ITA president Tarcisio Celestino, evaluated and chose finalists to move onto the second evaluation stage, which will be held at the 13-16 November conference in Paris. (Full disclosure: each year the panel of judges includes a rotating member of the tunnelling media and editor of *Tunnels & Tunnelling International* Alex Conacher is this year's representative.)

MAJOR PROJECT OF THE YEAR (over EUR 500M)

- Confederation LRT line – Canada
- Delhi Metro Phase 3 expansion of networks – India
- Qatar Rail Metro – Qatar
- Tehran Metro Line 6 – Iran

PROJECT OF THE YEAR (between EUR 50M and EUR 500M)

- Blue Plains Tunnel – US
- Citybanan, B4-9523 Nonströmstunnel – Sweden
- MTR Shatin to Central Link (SCL) Contract 1103 Hin Keng to Diamond Hill Tunnels – Hong Kong
- Túnel Emisor Poniente (TEP) II – Mexico

PROJECT OF THE YEAR (up to EUR 50M)

- Fjærland hydropowerplants – Norway
- Southwark to City of London deep cable tunnel – UK
- Tunnel Kennedy – Chile

TECHNICAL PROJECT INNOVATION OF THE YEAR

- Construction of bifurcation section of underground expressway underneath residential area, application of enlargement/widening technology of TBM tunnel, first challenge in the world wide tunnelling industry – Japan
- Implementing BIM concepts to Karavanke tunnel – Slovenia

- Trenchless construction of pedestrian underpass using a rectangular box jack TBM at Thomson-East Coast Line Havelock Station – Singapore

TECHNICAL PRODUCT/EQUIPMENT INNOVATION OF THE YEAR

- Automatic drilling jumbo – Finland
- RowaTrain – Self-driving trackless supply logistic system – Austria
- Strength monitoring using thermal imaging (SMUTI) – UK

SUSTAINABILITY INITIATIVE OF THE YEAR

- Anacostia River Tunnel in Washington D.C. – US
- ITO Metro Station – India

SAFETY INITIATIVE OF THE YEAR

- BSCU SCL radial joint design – UK
- MineARC's Guardian remote Monitoring and diagnostics for refuge chambers – Australia
- Telemach Cutterhead disc robotic changing system – Hong Kong

INNOVATIVE UNDERGROUND SPACE CONCEPT OF THE YEAR

- Bostanci Intermodal Hub – Turkey
- Cavern Master Plan of Hong Kong – Unlock hidden land resources for sustainable city development – Hong Kong
- Underground cemetery in tunnels – Israel

YOUNG TUNNELLER OF THE YEAR

- Anthony Bauer – US
- Juan David Herrera – Colombia
- Michele Janutolo Barlet – France
- Roberto Schuerch – Switzerland
- Tobias Andersson – Norway

Contractor fined for Crossrail incidents

GREAT BRITAIN — The Bam Ferrovial Kier (BFK) joint venture has been fined GBP 1M (USD 1.28M) for three health and safety incidents on London's Crossrail project, one of which involved the death of a worker.

A spokesperson for the Health and Safety Executive said: "Southwark Crown Court heard Renè Tkáčik died after being crushed by falling wet concrete on 7 March 2014. Two other men were injured following separate incidents within six days of one another, on 16 and 22 January 2015. All three incidents took place in the tunnels around the Fisher Street area.

"Renè Tkáčik, 43 from Slovakia, was working on a

team enlarging the tunnel by removing rings of the existing pilot tunnel and spraying walls with liquid concrete. During this operation, a section of the roof collapsed, fatally crushing Mr Tkáčik."

On 16 January 2015 Terence 'Ian' Hughes was collecting some equipment from inside one of the tunnels when he was struck by a reversing excavator. He suffered severe fractures to his right leg and crush injuries to his left knee and shin.

Six days later worker Alex Vizitiu, who was part of a team tasked with spraying liquid concrete lining, was assisting with the cleaning of the pipes that supply the concrete. Due to a lack of communication one of the lines was disconnected and he was hit by pressurised

water and concrete debris. He suffered head and hip injuries as well as a broken finger and was hospitalised for six days.

A spokesperson for the contractor issued the following statement: "The BFK joint venture has been sentenced[...] in the Southwark Crown Court in relation to three Health & Safety Regulatory Breaches arising from three incidents that occurred on the Crossrail project between 2014 and 2015. BFK acknowledges and accepts the sentencing decision of the Court and is fully committed to achieving high standards of health and safety. It is with deep regret that these incidents ever occurred and BFK will continue to strive to achieve a working environment free from incident. We wish

to convey our sincerest sympathies to all the families, friends and colleagues of the individuals involved."

New Hochtief UK MD

GREAT BRITAIN — Lawrence Jackson has been appointed as managing director of Hochtief (UK) Construction after former managing director, Sally Cox, stepped down.

Jackson said, "I look forward to working with the Hochtief UK management team to build on the many successes of recent years and to continue delivering engineering excellence, innovation and value for our clients and the communities we jointly serve. Our focus will remain firmly on our current projects and the pursuit of new opportunities.

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Best in class equipment, state of the art technology platforms, and the most passionate talent in our industry make Normet the top choice for biggest jobs.



Left: With the support of Herrenknecht service personnel, between October 2014 and June two EPB shields (Ø 3,397mm) used by Porr on the Emscher Interceptor achieved performances of up to 177m per week and up to 582m per month. See news story, page 7

SHAFT SETTLEMENTS

This technical note relates to the Harding Memorial Lecture presented by Dr Barry New, Geotechnical Consulting Group, at the ICE on 18 January 2017

DURING THE SHAFT SINKING works for the London Power Tunnels National Grid carried out settlement measurements around shafts varying in outside diameter from 6.5m to a maximum of 16.4m. This note presents a summary of this data and suggests a simple relationship for settlement prediction for shafts of varying diameters in stiff cohesive materials.

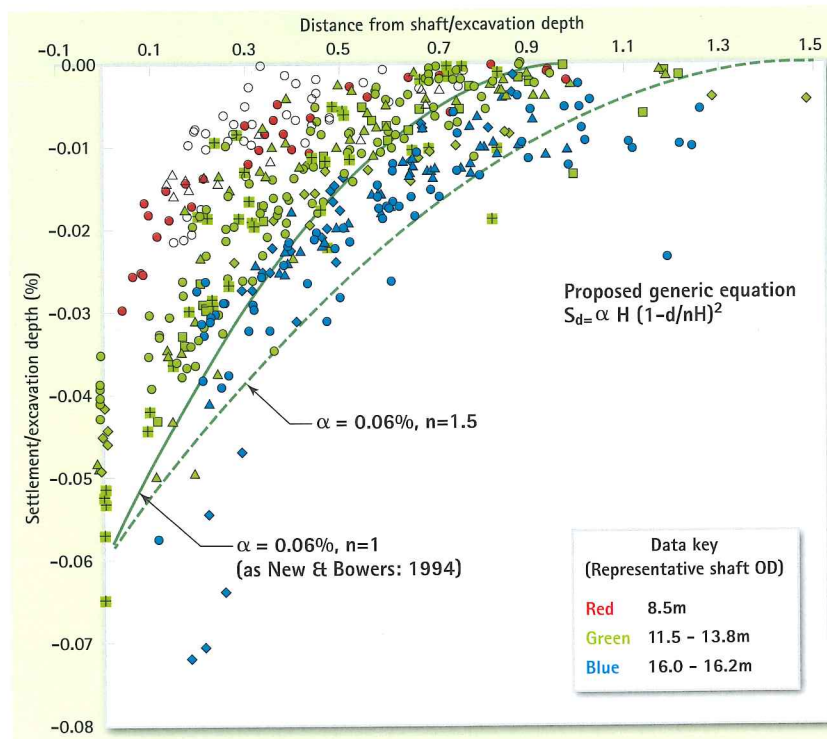
In 1994 New and Bowers published measurements of ground movements carried out during the works for the Heathrow Express Trial tunnel. These measurements included settlements around an 11m OD, 26m deep, segmentally-lined shaft into London Clay overlain with Terrace Gravels. Their equation provided a good fit with the Heathrow data but did of course rely on data from just one shaft diameter.

Since publication this equation has been widely used (and abused) and has been corroborated by measurements taken elsewhere for similar sized shafts in stiff clays. This technical note seeks to use the National Grid data to extend the predictive relevance of the relationship to shafts of varying diameters.

THE NATIONAL GRID DATA

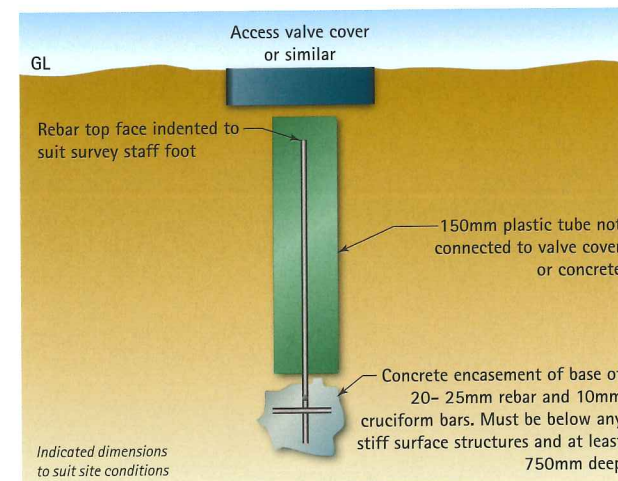
Figure 1 shows the settlement data from 13 shafts. The shafts were of similar construction as caisson segmental with sprayed concrete underpinning as required. Table 1 shows the location, size and depths of the shafts which were all in the London area and predominantly into stiff cohesive materials overlain by sands and gravels. The data has been assembled and synthesised as part of a wider study on circular shaft construction by Faustin (2017).

The data shown in blue were from the largest four shafts which were nominally 15.7m OD. Data in green were from eight shafts of nominally 11.1m and 13.2m OD and these are grouped together as there was no clear difference between them. The red data were from a single shaft of nominally 6.5m OD. The depths of the



Above: Figure 1, The normalised settlement data

Right: Figure 2, Sketch of shallow ground anchor



shafts varied between 26.5m and 47m.

The data shown as colourless points are from the two shafts at Kensal Green (13.2m and 15.7m OD) which showed what appeared to be anomalously low settlements: At present the reason for this is uncertain. There is a substantial scatter in the

data probably arising from the normal difficulties in obtaining data in urban environments close to major excavation works. In particular, the sites around shafts are usually heavily impacted by construction plant and other traffic and the measuring points are often mounted on pavement structures of varying stability.

The wide spread in the data makes analysis difficult but there is a clear trend that larger shafts tend, as might be expected, to produce larger settlements of greater extent.

PROPOSED PREDICTIVE EQUATIONS

The simple relationship derived by New and Bowers was:-

$$S_d = \alpha (H-d)^2 / H$$

(which may also be presented as $S_d = \alpha H (1 - d/H)^2$)

Where S_d is the settlement at a distance d from the shaft extrados. The settlement at the shaft wall is taken as αH where α is an empirical constant dependent on ground conditions, type of wall and construction method, and H is the shaft depth.

The curve was chosen such that the settlement becomes zero at a distance from the shaft extrados equal to the shaft depth and increases as the square of the distance from the undisturbed ground (at $d=H$) toward the shaft wall. At Heathrow the constant α was taken as 0.06 per cent to best fit the data and has proven appropriate at many other locations.

The same formulation may be extended to include a variable n which is a simple multiple of the shaft depth to a distance d from the shaft extrados where settlement becomes zero (For the New & Bowers equation this requires $n=1$).

The proposed generic equation for settlement at a distance d from the shaft wall is therefore:-

$$S_d = \alpha H (1 - d/nH)^2$$

The first derivative (slope)

$$\frac{\delta S_d}{\delta d} = \frac{2 \alpha}{n} [(d/nH) - 1]$$

The second derivative (curvature)

$$\frac{\delta^2 S_d}{\delta d^2} = 2 \alpha / H n^2$$

The radius of curvature $R = H n^2 / 2 \alpha$

(N.B. R is the minimum radius of curvature within the settlement area and occurs on a radius from the centre of the shaft)

There is currently insufficient field data to reliably predict horizontal movements which are commonly assumed to occur radially toward the shaft and to be of similar magnitude to the settlement.

CONCLUSIONS

The suggested generic equations may be considered by designers as predictive tools and the values of α and n chosen so as to reflect the degree of conservatism required of their assessment (i.e. conservative, moderately conservative, or best estimate): The values chosen should be supported by case history data suited to the shaft under assessment.

It must be noted that the data given in this note are derived from stiff cohesive materials overlain by various thicknesses of made ground and drift deposits (mainly sands and gravels). Elsewhere very different ground conditions will produce different results although the same equation may still be helpful. For instance, in Sao Paulo significantly greater and more extensive settlements (e.g. $\alpha = 0.23$ per cent and $n = 1.8$) have been indicated particularly in very soft to medium clays and where local dewatering had taken place (Dias et al, 2015).

There is an increasing use of diaphragm walls particularly

Table 1: Shaft location, outside diameter and depth

Location	Construction Method	Outside Diameter (m)	Depth (m)
St Johns Wood 1	Pre-cast SCL	13.2 14.4	45.6
St Johns Wood 2	Pre-cast SCL	6.5 10.6	47
Earls Court	Pre-cast SCL	11.1 11.9	39.5
Islington	Pre-cast SCL	11.1 11.9	37.6
St Pancras	Pre-cast SCL	11.1 12.0	44.8
Channel Gate Rd	Pre-cast SCL	13.2 13.1	32.9
Eade Road	Pre-cast SCL	13.2 14.2	39.3
Kensal Green 1	Pre-cast SCL	15.7 16.4	26.5
Kensal Green 2	Pre-cast SCL	13.2 14.0	42.7
Willesden	Pre-cast SCL	13.2 13.9	29
Highbury	Pre-cast SCL	15.7 16.7	35.2
Wandsworth	Pre-cast SCL	15.7 16.6	35.2
Wimbledon	Jacked caissons Pre-cast SCL	15.7 15.7 16.6	26.5

for larger diameter shafts and such developments are hoped to reduce settlements: However at present there is a very limited database and predictions are varied and difficult and more reliable data, particularly during wall installation, are required.

Where settlement is an important issue the wide scatter of results may be reduced if shallow ground anchors were used as a supplement (or replacement) to surface mounted road studs. A sketch of an anchor design as used at Heathrow and on other current major projects in London is given in Figure 2.

Acknowledgements

The settlement data in this technical note was originally published in the Harding Memorial Lecture by kind permission of National Grid – London Power Tunnels: The data being made available by Costain and Skanska, the main contractors for the works. The author is also most grateful to Njemele Faustin of Cambridge University for reviewing and assisting in data preparation.

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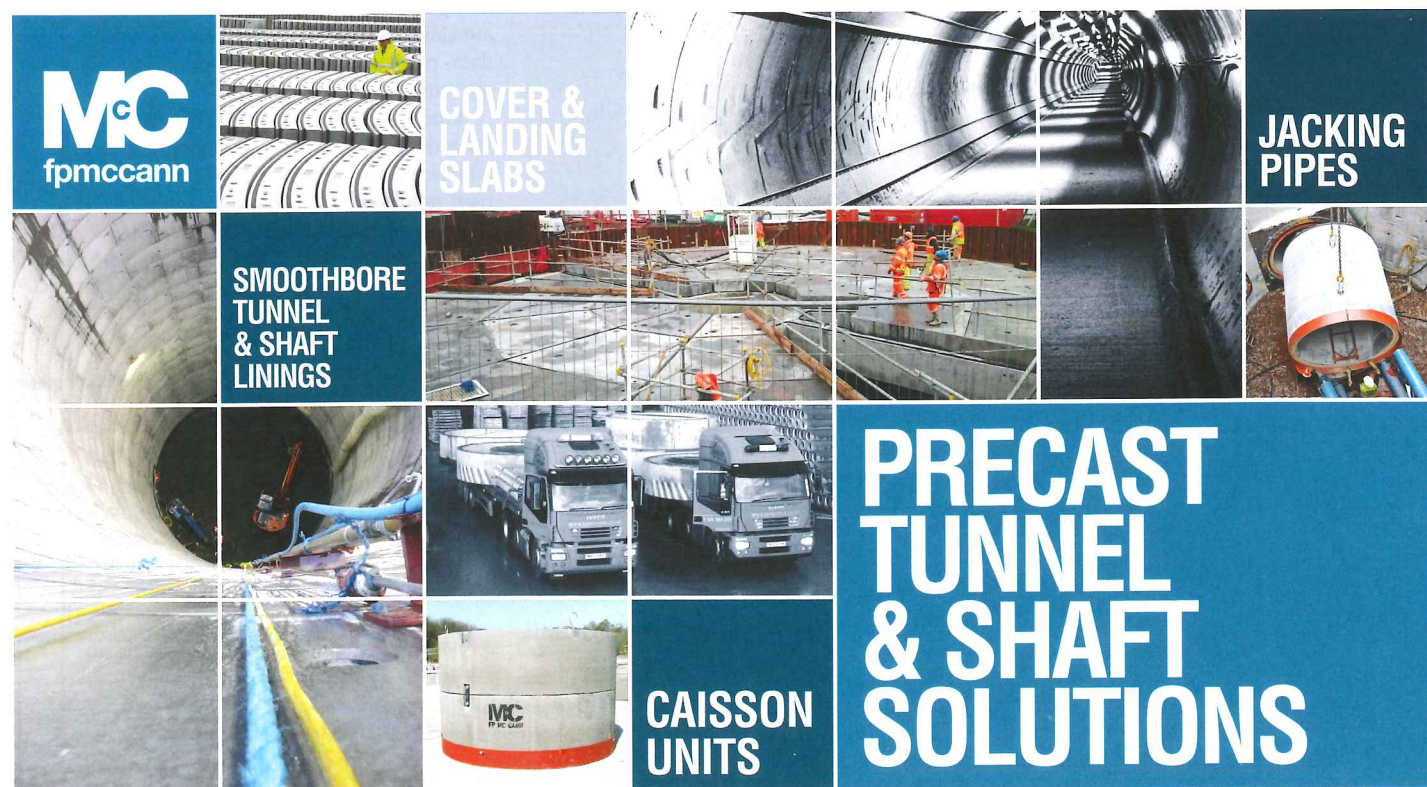
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JAMES CLARK WINNER

The BTS has recognised the life's work and contribution of Joseph Gallagher Ltd chairman Joseph Gallagher by awarding him this year's James Clark Medal. He talks to **Keren Fallwell** about his career

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WHEN JOSEPH (JOSIE) GALLAGHER was told he was to be awarded the British Tunnelling Society's James Clark Medal he received the news with characteristic modesty.

"You could have knocked me over with a feather because normally the people who receive the medal are at the top of blue chip companies, consultants, designers, people responsible for huge projects. For me to get it was a massive honour. It meant my peers thought I have made a contribution," says Gallagher.

As chairman of Joseph Gallagher Ltd (JGL), the largest tunnelling subcontractor in the UK, and with a lifetime's work in tunnelling, Gallagher has touched the careers of many so the accolade comes as no surprise to those who know him.

The James Clark Medal is awarded in recognition of a contemporary achievement in tunnelling, or innovation or responsibility for a large project, or a major contribution to the tunnelling industry. The BTS felt Gallagher easily fulfilled the criteria.

"In awarding the medal, the committee felt that not only were we acknowledging the enormous contribution that Gallagher has made to the tunnelling business but also providing a token of the contribution that the people of the west coast of Ireland have made," says BTS vice-chair Ivor Thomas.

Above: Gallagher is awarded the medal by BTS chair Mark Leggett

That contribution began when Gallagher was in his teens and now, at the age of 72, he has no intentions of hanging up his hard hat.

Gallagher was born on Arranmore Island in Co Donegal. Despite his head teacher's encouragement to pursue secondary education, Gallagher left school at 13 and moved to Scotland with his family where he worked on a farm. His introduction to civil engineering came at the age of 17 when he worked

Keren Fallwell
Keren joined the *Tunnels and Tunnelling* team in 2015 as a contributing editor



The James Clark Medal

James Clark worked for Charles Brand Et Sons on many well-known tunnels. He died in his early 60s and in 1981 his widow, Madeline, bequeathed a sum of money to provide a medal to be awarded annually to a British tunneller to perpetuate James's memory.

The criteria for the award are a contemporary achievement in tunnelling, or innovation or responsibility for a large project, or a major contribution to the tunnelling industry.

as a banksman to a crane on a reservoir project in Peebles.

In 1965 Gallagher moved to London and began his tunnelling career, working as a miner on the Victoria Line. In 1973 he took a job with Tim Kilroe in Milton Keynes and by the time he established his own company nine years later he had worked at everything from miner's labourer to miner, lead miner, pit boss and foreman – the latter at the tender age of 22.

HARD KNOCKS

In those early days it was an environment of tough labour and hard knocks.

"Production targets were very high and it was all done manually – there was no machinery at all," says Gallagher. "Even if you were a good worker it was difficult. You went through the pain barrier every day. You had to have a certain mentality to get through it and only the fittest survived." In contrast, today the hard physical work is done by machinery.

It was during these early years that Gallagher cemented his work ethic and the sense of fairness that are fundamental to his own integrity and to his company's culture.

And it was from Tim Kilroe, who recognised Gallagher's ability and promoted him to foreman, that he learned the skills of managing and motivating people.

"He taught me practically everything I know and man management was the greatest skill he taught me. His gift was when he was talking to you, you were the most important person in the world," Gallagher says.

When he started his own company he adopted not only the red and white livery of Kilroe's company, but much of the management style as well.

Until four years ago Gallagher was still doing the wages at JGL, which meant he knew the name of every one of the company's 1,000 employees. Since giving the role to his daughter and senior QS Claire, on subsequent site visits, which he still makes regularly, he was disappointed not to know people's names so now

everyone has their name on their helmet.

"It's important that your boss can call you by name. If he doesn't, you don't feel valued," says Gallagher.

The site visits mean an early morning start as Gallagher will have a cup of tea with people before they start work. "We'll talk about football, rugby – anything but work. My people aren't apprehensive to see me there; they're not overawed. If you can get people on side like that, the rest is easy," he says.

And everyone who knocks on Gallagher's door is treated with respect.

"Even those asking for a pay rise are treated with dignity. If I can't give them a pay rise I'll tell them why and if they're good at their job they'll get one next time and I will honour that. You must make sure they go away happy. If they go off unhappy you've lost an employee," he says.

Working for Tim Kilroe, Gallagher also learned the value of employing the "cream of men", an approach he emulated when Kilroe gave him his first subcontracting job and which he continued with JGL.

Gallagher established JGL in 1982. Thirty-five years later, that business is an GBP 80M- (USD 102.5M-) turnover international enterprise with five separate companies. It has completed more than 600 jobs, ranging from water infrastructure to a new connection tunnel for the Dorchester in London and many high-profile projects such as the Channel Tunnel Rail Link, Hindhead Tunnel and more recently Crossrail.

JGL's first sizeable job – and perhaps biggest challenge – was in 1988 with the GBP 11M (USD 14M) contract to upgrade Bank station in London to accommodate the DLR.

"It was one of the biggest challenges I faced," says Gallagher. "The biggest jobs we'd had until then were about GBP 300,000 and suddenly I won a contract for GBP 11M. I had 15 or so people working for me – all great people – but I needed 400."

Making it even more challenging was the fact the Channel Tunnel was being built at the same time, offering "colossal money".

"The project was too good to turn down and I decided if I was going to be successful it had to be on price work, not day work. There wasn't one person on day work and I set all the prices myself," says Gallagher.

From here JGL continued to grow and expand. In 1990 Gallagher bought Specialist Plant Associates, the only company in the UK to own and operate compressed air tunnelling equipment for rental.

Seven years later JGL purchased NRC Plant, the UK's second largest crawler crane hire company. It is the sole agent in the UK for Hitachi Sumitomo in Japan and Link-Belt in the US.

In 2007 Japanese company Iseki Microtunnelling was added to the group. The purchase presented another case where Gallagher's aptitude for tackling problems was required.

"We had about 30 microtunnelling machines and six months after buying the company the bottom fell out of the UK market," explains Gallagher.

The answer was to go to the Middle East and Iseki now has offices in Kuwait, Bahrain, Oman and Dubai.

The most recent addition was Johnston Trenchless Solutions, purchased from Carillion in 2008. It has a strong presence in northern England and Scotland and undertakes similar work to JGL but on a smaller scale.

JGL has worked for Costain for 30 years and has many other repeat clients. One of the things Gallagher is most proud of is that the company has never lost a client.

"If we failed to get a client's repeat business I would consider we'd failed," said Gallagher.

Fair play and honesty have been integral to his relationships with his clients, and he instils the same in his staff.

"With clients we have our ups and downs like any marriage but I will not tell them a lie. It may be uncomfortable for me but they know they can trust me. It's not all about walking away with all you can; it's about trust and repeat business," says Gallagher.

"I teach my team to be honest. If you make a mistake, hold your hand up and people will respect you."

Gallagher's reputation for expertise and honesty mean he has often been called on in emergencies. In the early 1980s he became a reluctant celebrity when he was involved in a recovery operation in a sinkhole on the Isle of Wight. It was a treacherous task. Gallagher and his two colleagues decided to sink a shaft but there was an 80ft (24m) cliff adjacent to the hole and machinery was hard to come by on the island. The team completed the operation in about six days, with the world's media watching from the sidelines. On the second day Gallagher emerged from the shaft to find Kate Adie from the BBC ready to interview him.

A few years later, on a Friday after, he had a call from a company that was sinking a shaft near Land's End in Cornwall. The shaft had flooded and they needed Gallagher's help. Gallagher and his team were there first thing on Monday morning and remedied the situation – "no contract, nothing on paper, just a handshake", Gallagher recalls.

In 2014 Gallagher appointed a managing director – Steve Harvey – and took the role of chairman.

"For me that was the biggest day in the business since I formed the company because the next day I wouldn't be making the decisions," he says.

He's happy, however, that Harvey is continuing the culture of fairness. "Steve works very hard; everyone respects him," says Gallagher.

At the same time, the next generation of Gallaghers has joined the business. One of his sons, Paul, is managing director designate, Claire is senior QS, Sinead is office manager, and son-in-law John O'Dwyer is contracts manager.

The change in role has enabled Gallagher to champion JGL's health and safety programme. Having started work in an era when health and safety was not a priority, Gallagher is passionate about it.

"In those days you put your life on the line because production targets were everything and your safety was secondary. We were motivated by they money: get the job done, get your weekly salary and forget about the consequences," he explains.

He is the first to admit that as a younger man he took risks. "How long have you got? I did everything in the book because that was the culture in my day," he says.

But the mentality has changed and Gallagher wanted to ensure JGL had the right health and safety culture.

"I took it on to show the workforce how important health and safety is," he says.

About two years ago the company brought in Alkoomi, a behavioural safety leadership specialist, to understand people's behaviour and how to work with it to initiate change.

The result is the group-wide LIFE (Living Incident Free Everyday) programme. Key to it is that managers lead by example, and everybody has mutual respect, aware that their behaviour can affect others working with them.

A large part of its success, says Gallagher, who attends every training workshop, is the fact that the 44 trainers (and another 10 in the pipeline) are from the JGL workforce.

"They train their workmates, and that's very powerful because they know the person who's training them. The trainer has to lead by example and work safely himself. It's training by example," says Gallagher.


There is also further motivation to remind the workforce of health and safety practices. A health and safety best practice award is made on every site every week and the winner receives a GBP 50 voucher. JGL also operates a system of "observation cards" where if a worker isn't happy with something they can write it on a card and pass it to their manager. For every card received JGL donates GBP 1 to the winning site's chosen charity.

"The programme motivates the workforce to behave wisely and make the right choices," he says.

AWARD

This ability to inspire and lead people, to command respect and give respect, and to deliver work fairly and honestly, are the attributes the BTS recognised in awarding the James Clark Medal.

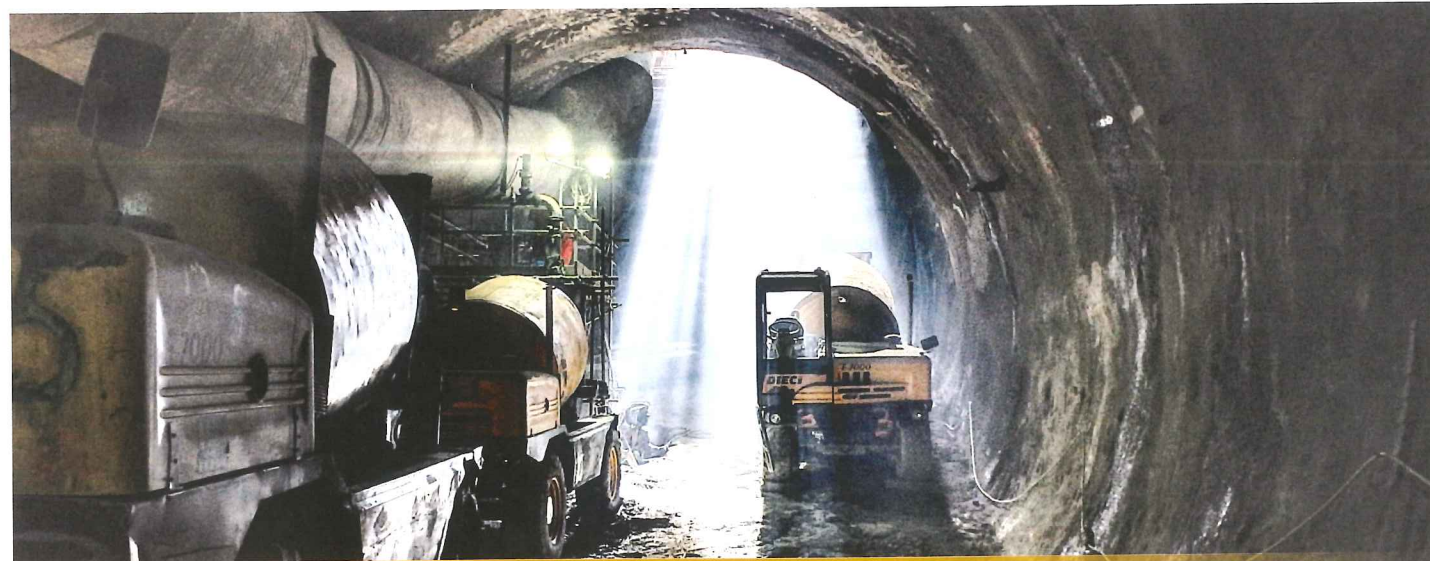
Presenting the medal to Gallagher, vice-chairman Thomas said: "Whoever has worked with Gallagher over the years will appreciate his work ethos on all projects, however big or small, the camaraderie he instils, not only in his own team but which extends to the clients he works alongside, and his innate ability to find ways to move a project forward in even the most trying of circumstances. It is this ability and his determination to succeed that makes his service to the construction field, be it tunnelling of all diameters, lengths and methodologies, reinforced concrete frames or heavy civils, almost unparalleled.

"Gallagher has served the tunnelling industry for over 48 years and is still as passionate and determined as ever to be at the top of his game. As attested by people who have had the privilege to work with him, Gallagher is a true inspiration." 



MAIR TAKES ICE PRESIDENCY

Paola De Pascali met with Lord Robert Mair to discuss his life and times as he prepares to take up the presidency of the ICE in 2018



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STUVA

“How feasible would it be to construct tunnels close to tall buildings?” That question was whirling through my head and I wanted to provide an answer,” says Lord Robert Mair, who has been professor of geotechnical engineering at Cambridge University since 1998 and throughout his career has specialised principally in underground construction.

“After graduating in 1971 from Cambridge University, I got a job with Scott Wilson Kirkpatrick, which was a large consulting company. When I was 23 they sent me to Hong Kong to work on the design and construction of a huge container port – nothing to do with tunnels at that point in my career.

Above: The Institution of Civil Engineers turns 200 next year

“At that time in Hong Kong there was no metro at all, but the government was beginning to think about it. There was a lot of concern regarding the feasibility of constructing tunnels close to tall buildings and in complicated soil conditions too.

“I was very fortunate because I was in the right place at the right time. Scott Wilson sent me back to Cambridge to undertake research on centrifuge modelling of tunnel construction in soft



Above: The Mythe Bridge over the River Severn, reported to be Telford's favourite project for aesthetic reasons

ground. The Tunnels Division of the Transport Research Laboratory (TRL), headed by Myles O'Reilly, funded this project and I was awarded a PhD at Cambridge University for this work in 1979.

"That changed my life. My early involvement with tunnels began at that time. Maybe if I had not been in Hong Kong, I would still be designing container ports and other things."

MOVE TO SOFT GROUND

Tunnelling in rock obviously has challenges, Mair explains, these mainly relate to machinery and cuttability. "When tunnelling in rock, you don't normally get movements," he says. "Instead with tunnels in soils you have to check the stability and movements to make sure the tunnel doesn't collapse. Movements of the ground above or around the tunnel are particularly important in urban environments. That was the area in which I started to work."

Mair was responsible for the introduction of compensation grouting in the UK as a novel technique for controlling settlement of structures during tunnel construction.

"Compensation grouting has been hugely effective in managing the risk of potential damage to buildings," he says. "It is a technique that we first introduced on the Waterloo Escalator Tunnel."

When the Channel Tunnel was completed between France and the UK the first station in London was at Waterloo (subsequently it was replaced by

a new station at St Pancras). Consequently there was a lot of new infrastructure works at Waterloo station, including a new 8m-diameter escalator tunnel, which was to be constructed very close beneath some buildings at Waterloo, mainly the Victory Arch, the main entrance to the station.

"This escalator tunnel was also going beneath the Waterloo and City Line, which is a very old London Underground tunnel. London Underground asked my consulting company, Geotechnical Consulting Group (GCG) how could we construct this escalator tunnel without causing these two important and fragile pieces of infrastructure to settle significantly. The Victory Arch has marble finishes and is very sensitive to movement and the Waterloo and City Line is an old masonry tunnel built by the Victorians.

"The escalator tunnel was big – 8m in diameter – and the potential settlements were around 100mm, so we conceived the concept of compensation grouting for that project. The principle of compensation grouting is that before the tunnel is constructed, tubes are installed in the ground before any tunnelling commences; then, during the tunnelling grout is injected from specified holes in the tubes to compensate for the ground movement caused by tunnelling. By this means, combined with comprehensive monitoring, you can prevent the ground movements caused by the tunnelling from propagating up to the building. So you can control the differential movement of the building. That was very successful and we named the process 'compensation grouting'.

Its first trial in the UK was at Waterloo station and when it was proved successful, it was used widely for other projects, most recently for Crossrail in London. Compensation grouting was subsequently adopted for the Jubilee Line Extension project.

"The big ground movement challenge for the Jubilee Line Extension project was to protect Big Ben. Compensation grouting was adopted for protecting the clock tower at Westminster – this was very high profile.

"Without this protective measure Big Ben was predicted to lean too much. The compensation grouting was very successful in controlling the movements of the tower and protecting it from damage."

ICE turns 200

In 1818 three young engineers met in a London coffee shop and founded the Institution of Civil Engineers (ICE), the world's first professional engineering body.

After a couple of years, the ICE asked Thomas Telford to become its first president.

"Thomas Telford was a remarkable man," Mair says. "He came from a very humble background. His father was a Scottish shepherd and he grew up not well educated at all. When he became the first president of the ICE, he was already responsible for numerous bridges, roads, canals, tunnels and much infrastructure throughout the UK. He was an amazing man who was not afraid of pushing the boundaries to instigate new works."

In his lifetime Telford constructed more than 1,000 miles of highway and was nicknamed 'the Colossus of Roads'.

The London to Holyhead road is among

his most well-known projects and included the Menai Suspension Bridge. This was the longest suspension bridge of its time, spanning 180m across the Menai Strait, to link North Wales with the island of Anglesey.

With his reputation growing, Telford was asked to build the Ellesmere Canal, which involved constructing the Pontcysyllte Aqueduct across the River Dee.

Telford had to come up with a fresh way to seal connections to its iron plates, using boiling sugar and lead.

To celebrate its 200th anniversary, ICE is promoting publicity about engineering projects that have transformed society across the UK and internationally.

The aim is not only to celebrate civil engineering, but to leave a legacy to inspire the next generation of engineers.

The story behind each project will be told using a variety of media including short films, case studies, and a global interactive map on the ICE website. A 'coffee table' book will also

be produced featuring photographic images and inspirational stories.

A brand new exhibition is also planned to showcase content from the ICE 200 programme at ICE's Visit England-accredited Infrastructure Learning Hub, currently home to the tunnelling exhibition.

ICE director of engineering knowledge, Nathan Baker, says: "This is an exciting opportunity to explore the people, places and projects that have transformed the lives of communities across the globe. Civil engineers contribute a huge amount to society and yet not everyone knows the story of how, what or who helped to shape the fabric of modern civilisation. They are what you might call 'invisible superheroes'."

"The ICE 200 programme will tell these stories, looking at engineering greats and major engineering feats. It will also look ahead at what civil engineers will do to help shape the future of society in a new digital era," Baker says.

THE FUTURE FOR TUNNELLING

Regarding changes to the tunnelling industry throughout his career, Mair says the biggest development has been the pressurised tunnelling machine, in particular EPBMs and slurry shields. "Because of those major developments, it's now routine to be able to create tunnels in all soft ground conditions with very low volume loss, which is the cause of ground movements," he explains. "Over the last decade or two, we have seen progressive reductions in volume loss."

As for the future of tunnelling, "I think that there are a lot of opportunities for creating underground space, especially with a worldwide increase of urbanisation," Mair says. "It is well-known that by 2050 the world population will be around nine billion, with two-thirds of that population will be living in cities. That means six billion in cities. It's interesting to go back to 1950 when the world population was around three billion and only one third was living in cities. So in 100 years we have seen urban population growth of six times. The pressure on engineers is to create cities that can accommodate all these people, and of course that means more tunnelling."

"I'm very optimistic that tunnelling has a major role to play in the urban environment. Soft ground tunnelling is particularly significant because most big cities in the world are located either on the coast or on rivers. This usually means that the ground is quite soft because coastal and river geology is more often soft soil than rock. A high proportion of the cities of the world are therefore on soil – at least in the upper layers of the geology – and often this will involve quite soft soil conditions. Of course there will also be rock beneath cities, but the majority will be in soils."

Beyond conventional uses of tunnelling such as transportation and water supply, Mair sees other opportunities such as underground living or underground storage. "The possibility to use underground space is becoming increasingly attractive for environmental reasons," he says.

Mair explains that nowadays there are new means and technologies to create tunnels without causing any problems to the surrounding urban environment. "The use of SCL is another important development. SCL was originally used for rock, but

over the last 20 years the technology to use sprayed concrete linings in soft ground has really changed. SCL is now used extensively in soft ground and the Crossrail stations are a good example of this. Most of these stations are in London Clay, but Farringdon Station was in much more difficult ground conditions with clays, sands and a lot of faults. So there were originally concerns about the use of SCL in such ground conditions, but by controlling the water really well they managed to construct the tunnels in very stable way and it was very successful. With the right measures to control water pressures, SCL can be used in difficult and even potentially unstable ground."

ACHIEVEMENTS

"I'm very proud of the reputation that the Geotechnical Consulting Group has. I founded this consulting group when I was in my early 30s, and that was a very exciting new phase in my life. I am delighted that GCG still flourishes today," Mair says. "Regarding the projects I am most proud of, it's really hard to choose, but I think that I would go for the Jubilee Line Extension project and the Crossrail project. I'm honoured to have been part of both projects. Of course I have been involved in other jobs in many parts of the world and I have a lot of good memories of the different challenges."

"I think I prefer these two projects because I spent most of the time on them, and because GCG was closely involved in both of them. For the Jubilee Line Extension I was working full time at



Above: Robert Mair is set to become ICE president

that time and then, in 1998 I changed my life and became an academic at Cambridge. Regarding Crossrail, it was a different kind of involvement because I was a member of its Engineering Expert Panel. On Crossrail there was also a good opportunity for my research students because I lead the Centre for Smart Infrastructure Construction (CSIC) at Cambridge, which pioneers innovative sensor technologies for monitoring performance of infrastructure such as tunnels."

He was awarded a CBE in the 2010 New Year's Honours list and appointed an independent crossbencher in the House of Lords in October 2015.

BRITISH TUNNELLING MARKET

"I think that the strength of the British tunnelling market worldwide is very high - there is a strong influence of British tunnelling in many parts of the world," Mair says. "For quite a long time I co-chaired the International Advisory Board on Underground Construction for the Singapore government. In Singapore they have a great number of tunnelling projects, probably the equivalent of at least two Crossrails under construction at any one time.

"In the UK the tunnelling market is, as in many places, heavily dependent on the

government. The current projects are Crossrail, Thames Tideway and HS2- they are all a great opportunity for the British tunnelling industry.

"For the future I think that UK government will only support a new tunnelling project if the cost-benefit analysis is positive. For example there are some countries where governments are actively supporting tunnelling projects, but this is not happening in the UK. We currently have a much tougher economic and political environment than many other countries and the uncertainty around Brexit is not good for the construction market. I believe that Brexit is bad for many reasons. An example is the high proportion of European skilled engineers and technicians who have been working on Crossrail. We have got a lot of really good Spanish, Italian, French and German engineers currently working in the UK. But also many of the construction workers are from a large number of different countries in Europe. We will have to see how Brexit ends up; of course there is a real concern. But for sure we need their expertise because the tunnelling community is very international."

PLANS FOR ICE

For Mair, the current year is the last as a full-time academic at Cambridge, and in 2018 he will be president of ICE.

"The main theme for my presidential year at the ICE is its 200th anniversary," he says. "It was founded in 1818 and so there will be a lot of focus on the huge achievements of British Civil Engineering over the last 200 years. The real emphasis will not be on the past, but on the future.

"This is the opportunity for exciting new technologies to really change the way that we are doing a lot of civil engineering. At Cambridge CSIC has developed some really innovative smart technologies including wireless sensors, fibre optics and computer vision. These smart technologies will have a big influence on the way we design, construct and operate our infrastructure, not only tunnels.

Civil engineering has the reputation to be old and slow, but it is becoming much closer to being fast and new, like the aerospace and manufacturing industries - largely thanks to the digital revolution. It's the time to make a big difference to civil engineering."

In terms of challenges for the ICE, Mair says it is fundamental to give value to its members and to continue to make a big difference to society.

"We have around 90,000 members all around the world. It's important that the Institution remains relevant to them, providing value to them and giving them the kind of things that they need to know," he says.

"The Institution is very much keeping abreast with all the latest development and technologies, producing reports on the latest developments, providing opportunities for members to keep abreast of the new things going on. It's important for the Institution to remain modern, relevant and useful to its members. The British Tunnelling Society (BTS) is an example of one of the most vibrant parts of the activities hosted by the ICE. There are always very active BTS meetings at the ICE, which are very well attended."

Mair adds that the biggest achievement of the ICE is the sharing of knowledge.

"For example when you need to know some details about a past tunnel project, you can come to the ICE and search the Proceedings - there is likely to be a detailed account of the project, which includes invaluable information.

Sponsored by Ferrovial Agroman and others, the ICE is hosting a superb tunnelling exhibition until this November, showing some of the longest, deepest and most advanced tunnels in the world. ☺

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ANDEAN POTENTIAL

From hydropower and metro systems to mining and road tunnels, Chile's tunnelling market remains buoyant and some major projects are on the horizon



Above: NATM was used for construction of 37km of new tunnels on Santiago metro Lines 3 and 6



Bernadette Ballantyne
Bernadette is an engineer and freelance technical journalist

RUNNING 4,300KM NORTH TO south along South America's western coastline, Chile is one of the region's fastest growing economies and remains one of the most attractive investment markets in South America ranking number 16 in the Arcadis Global Infrastructure Investment Index.

Like its economy its infrastructure is growing as improving transport, connectivity, and power generation capacity is vital to service the demand. "The market is quite active now, as there are



Above: The Santiago skyline in winter
COURTESY OF LIEBHERR CHILE

some really interesting projects under development and coming in. There are road projects, metro projects, hydropower projects and mining projects," says José Miguel Galera, managing director of consultant Subterra, which has been designing tunnels in the country for more than 20 years and does 50 per cent of its business in Chile.

The firm is currently involved in three major road tunnel projects. The second stage of the Santiago Centro Oriente Project is currently under construction. This project involved the expansion of the east-west connections across the city. An existing 5.5km tunnel provides some capacity but another four tunnels are required to serve the growing traffic demand. The most high profile of these is the new 1.1km Túnel Kennedy, which is due for completion at the end of 2017 and was the subject of a detailed report in *Tunnels and Tunnelling International* in May.

For its design the priority has been the minimisation of induced settlements on the surface. The new road will run partially beneath a golf course alongside the existing Kennedy Avenue. To ensure the existing infrastructure was not affected the designer undertook numerical modelling focusing on the stresses acting on the support elements and the induced settlements.

Construction of the tunnel is being undertaken by Sacyr Chile and Gesival under a USD 500M contract. The excavation method is a bespoke version of NATM, or sequential excavation method, which is necessary due to the extra-large cross section of the tunnel, which measures 22.9m across and is 13.5m high. Depending on the geometry the top heading is excavated using two or three side drifts, while benching was always excavated using three phases. The excavation has been done using hydraulic excavator, backhoe and wheel loader.

Subterra is also undertaking design and construction supervision on Tunnel Chamisero 2, part of the north-west motorway known locally as Radial Nororiental, where a second 1,600m tunnel is being built alongside an existing passage to increase capacity.

But the largest scheme that it is working on is the missing link of the Americo Vespucio highway, which is a privately financed concession road running around the perimeter of Santiago. The first 65km of ring road is operational but the most challenging eastern section is now in the design phase. "It has been divided into two contracts. Americo Vespucio Oeste 1 (AVO1) is a 9km tunnel and we are the designers in joint venture with Louis Berger from North America. The second one is just 5km and concessionaires are bidding for it," says Galera. This includes a Chinese consortium, which adds a new dimension to the tunnelling industry as Chinese firms to date have not

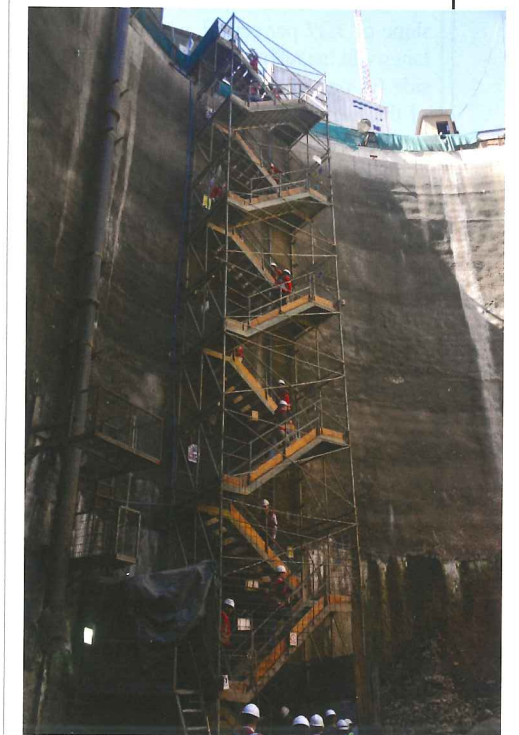
undertaken this type of work in the country.

The 9km section involves 3km of conventional drill and blast tunnelling beneath a hill known as the Cerro San Cristóbal and the other 6km is a mixture of cut and cover, the traditional German method and NATM. The concessionaire for the project is OHL Concesiones in consortium with Sacyr Concesiones and the route runs through five communities and beneath the Mapocho River. Construction is scheduled to start in January 2018.

NEW HORIZONS

But perhaps the most exciting road tunnel for Chile will be the Paso de Agua Negra road tunnel running between Chile and Argentina and promoted by a joint

Right: Construction of the new line 6 between Los Leones and Cerillos



governmental organisation known as Ebitan. "All tunnellers are positioning ourselves for this really interesting project. They called for prequalification at the end of 2016 and just two months ago it was published that 10 JVs have presented their candidature and four are Chinese. The other six are from the rest of the world," says Galera.

The scheme involves construction of twin 14km road tunnels and is intended to improve regional connectivity particularly between Argentina and Chilean ports. Despite the enormous length of the Argentinian and Chilean border the number of crossings is small and largely consists of minor roads. The existing Agua Negra route for example is a minor road used just in summer as it runs along an altitude of 4,780m meaning that snowfall blocks the route in winter months.

The new tunnel will be around 1,000m lower and is planned as a twin tube due to its length and height. A second passageway offers many safety advantages and by having two equal tubes natural air circulation is enhanced reducing energy costs. It was also decided that each tunnel as a single lane is much safer from a driver perspective. With two tunnels and one-way direction each, light vehicles might keep a good speed and are not delayed by heavy traffic taking the outer lane.

The two tunnels will be 40m to 50m apart and descend from Argentina into Chile with the Argentinian entrance 4,085m above sea level and the Chilean entrance at 3,620m giving the tunnels a slope of 3.37 per cent. Each of the road lanes will be 7.5m wide with space either side for pedestrians. The internal height of the tunnels will be 4.8m and emergency tunnels for people will connect both main tunnels at 250m spacings along the whole length. Vehicular interconnection galleries will be located every 1,550m.

The industry is now waiting to hear who the successful prequalifiers will be and whoever ultimately wins this project will undoubtedly take on lessons from other tunnelling projects that have been carried out in the Andes including a raft of hydropower schemes. The most recent of these are the Alto Maipo project and the Los Condores project, which both include significant tunnelling works for construction of the headrace tunnels and other infrastructure.

ROCK HARD

AES Gener and Antofagasta Minerals are responsible for the USD 2bn Alto Maipo hydropower project situated in the Andes



Above: View of a shaft bottom on the Santiago metro project

approximately 70km south of Santiago. The project involves around 67km of tunnelling to transfer water from the Maipo River into two caverns where the flow will generate 531MW of hydroelectric power.

The country has generally favoured traditional methods of drill and blast and NATM, but this scheme has been a testing ground for the use of TBMs in Chile. As far as testing grounds go, the Andes are a tough place to start.

Challenging conditions have contributed to a number of issues on the project, which is running over budget and has led the client to terminate the AM-CO 610/620 contracts awarded to contractor the CNM joint venture. This was a pairing of Germany's Hochtief through local subsidiary Hochtief Construction Chilena and Italy's Cooperativa Muratori & Cementisti di Ravenna (CMC), and was cancelled in June due to what AES Gener states in its Q2 financial report for 2017 were "breaches of contract by CNM".

This led the client to take control of the works to continue progress and Robbins is running its TBM until a replacement contractor is appointed. At the same time, the client has drawn on the USD 73M Letters of Credit posted by CNM and CNM and the Alto Maipo client have now entered into judicial and arbitration proceedings. Both AES Gener and CNM declined to comment on the current situation.

However, AES Gener states in its Q2 report that termination of the contract triggered a technical default and the project finance disbursements have stopped until a replacement contractor is found. Negotiations for this are ongoing and could see the main construction contract restructured. Depending on the forward strategy, and potential new delivery date project costs are likely to increase.

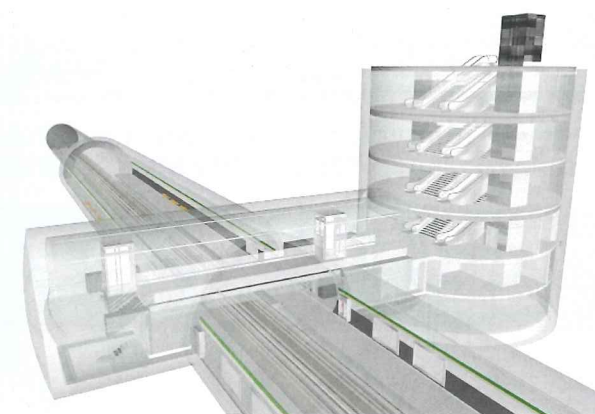
CHALLENGING TUNNELLING

On Alto Maipo the CNM joint venture was undertaking mechanised tunnel boring in two key sections using the same 4.13m diameter Robbins open gripper type hard rock TBM fitted with 17 inch Wedge Lock back-loading cutters and 267kN nominal load capacity each. The intention was that it would first be used to bore an initial 7km section, which was at the south end of AM-CO 620 contract, before being disassembled and moved back along the tunnel to then be used to bore a 3km section to the north of the contract area. In a white paper describing the project Robbins tunnelling experts Carlos Lang, Mark Belli and Pablo Salazar explain the progress and the issues encountered underground.

Tunnelling began in June 2015 making good progress with 106.33m achieved in 15 days thanks to the good to fair quality of the rock mass, composed of andesitic breccias with signs of



Above: New trains ready for Line 6 operations



Left: Typical new station layout for Santiago metro line 6 expansion

alteration. But the rock quality deteriorated as the work progressed with sub-horizontal joints and faults continuously detected leading to continuous over break and the need to employ the full remit of rock support (Type I- to Type IV) and ultimately installation of the bespoke McNally support system used for Robbins TBMs.

This system prevents rock movement in the critical area immediately behind the cutterhead support. Shield fingers are switched out with a curved assembly of pockets with rectangular cross-sections. The pockets extend axially back from the rear side of the cutterhead through the support, in the area where roof drills could work.

"Standard ground support measures were applied to handle these sub-horizontal joints in the initial drill and blast excavation but this became a serious problem for a small 4.13m open type TBM that in principle had been selected for good rock conditions. Under difficult ground conditions the TBM operation demanded continuous manual scaling and manual mucking in order to remove loose material caused by wedges formed from these sub-horizontal joints in the tunnel crown," write the Robbins authors, who also note that the sub-horizontal structures contained along the excavation were not outlined in the geological baseline report.

These difficult ground conditions led to a number of improvements to be made to the TBM including an extension of the side supports and the vertical front support to better face extreme squeezing ground conditions; a new probe drill set up; a mechanical system for removal of the large blocks in the invert area, a new dewatering system, new storage areas and a more user friendly shotcrete robot set up to reduce rebound.

To accelerate progress the client has now ordered a second

open gripper main beam TBM to use on the project.

On the Los Condores 150MW hydropower project owned by Enel Generación Chile, a 4.56m double shield TBM is being used for a 12km intake tunnel, under construction by contractor Ferrovial Agroman. This was launched in February 2016 and has bored more than 1.2km of tunnel in sandstone, tuff and pyroclastic breccias. Again the ground conditions have been challenging and unexpected, and a very large inflow of water and running ground has made it impossible to consolidate the ground from inside the tunnel leading to the need to construct a bypass tunnel to continue work.

METRO EXPANSION

Meanwhile in Santiago the metro system has been the beneficiary of significant investment in recent years. Originally opened in 1975, the client Metro de Santiago is just about to open a newly constructed Line 6, which will connect seven municipalities into the public light rail system. There are more than 15 km of underground tunnel, and 10 stations, of which four will be combined stations with existing operational lines and two will connect with the urban train between Santiago and Nos.

At the same time the new 22km extension to Line 3 is also approaching completion. Like Line 6, the project will have fully automated trains and was constructed using NATM. The circular diameter of the tunnels is 25m, with 15m diameter ovoidal access galleries and stations.

According to the client Metro de Santiago the main construction challenges of Lines 6 and 3 have been delivering the new lines without affecting existing operations, particularly in the nine locations where the new lines meet the existing ones, and in addition to that the construction of the combination station Ñuñoa with tunnels of Line 3 on the tunnel of Line 6.

A total of 700,000m³ of concrete has been required for construction, with two-thirds of this shotcrete and one-third reinforced concrete.

Looking ahead the next major tunnelling opportunities on the city's metro system are expected to be extension of Line 2 and a new Line 7.

Reference

www.therobbinscompany.com/white-papers/2017/06/05/andean-tunnelling/



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BONDING WELL

To repair a limestone block tunnel more than 120 years old, a local watershed agency and its engineering consultant devised a solution using shotcrete to create a tunnel in a tunnel. **Nicole Robinson** reports on the Trout Brook Storm Sewer Interceptor's rehabilitation



Above: The TBI with water bypassed and construction lighting in place

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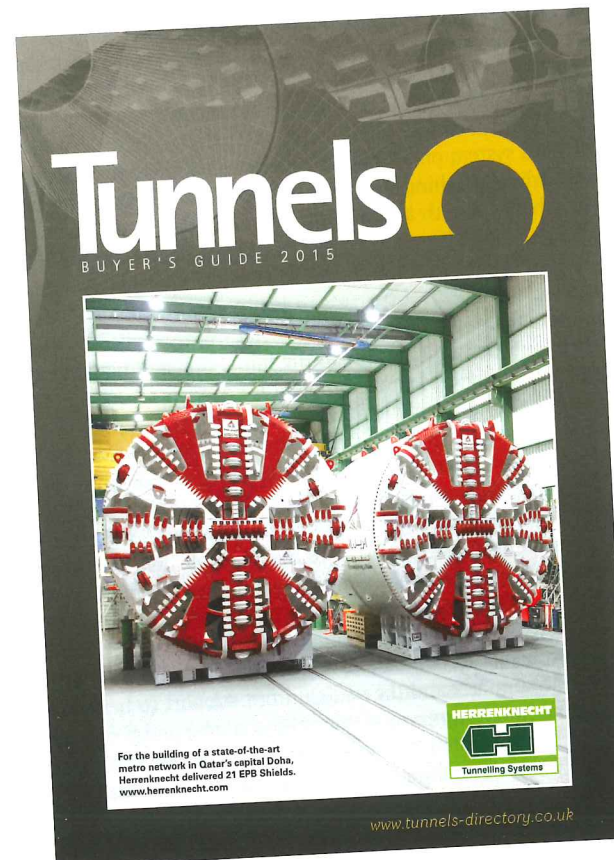
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Nicole Robinson
 Editor of *Tunnels and Tunnelling North America*
 Nicole has been with the magazine since 2010



IN TODAY'S WORLD A major interstate highway and other modern transportation infrastructure criss-cross the once picturesque ravine called the Trout Brook Valley located in Saint Paul, Minnesota. Some 300 years ago this area had an actual brook and was home to the Mdewakanton

Testing



The 12-inch-thick overlay coring test panels
Vertical and overhead test panels to certify the nozzlemen and their processes confirmed methodology and the absence of shadowing and voids



The 2-inch-thick overlay load tests
Pull testing verified a good bond for the mix sprayed directly onto the existing blocks—a crew member applies pressure trying to pull away a cored circle of the overlay

Dakota that depended on its fertile ground as both a source of food and a transportation corridor.

In the early 1800s as Europeans began settling the area for farming, they started filling in the brook, as well as using it as a power source for their mills. Shortly after the 1880s and the arrival of the railroads, it was decided to bury the Trout Brook entirely. "It was becoming an area that was receiving a lot of raw sewage and rainwater runoff. It became an impediment to transportation but also a health hazard," says Anna Eleria, a division manager of the Capitol Region Watershed District (CRWD), which owns and operates the tunnel.

The Trout Brook Sewer Interceptor was built by cut and cover in 1888 for USD 84,000 (about USD 2.1M today). "We actually have a copy of the contract document between the City of St Paul and the contractor," she says.

The 10ft- (3m-) diameter, 2,500ft- (762m-) long storm sewer comprises limestone blocks and with granite and brick pavers in the invert. As the city grew during the 20th century the Trout Brook sewer grew too to six miles (9.6km) in length, constructed in phases with the last work dating to the 1950s.

Cover ranges between 3ft and 6ft (0.9m to 1.8m) along the alignment, which includes a stretch crossing beneath four active railroad tracks. In some places limestone blocks are being dislodged or displaced. Routine inspections carried out every five years also showed mortar degrading and leaving gaps.

A repair program this winter focusing on the original sewer section replaced the mortar and improved the structural integrity of the tunnel. The project team

adapted its solution to accommodate the historic limestone, and retained much of the tunnel's original aesthetic.

INSPECTION RESULTS

As a CSO, the previous owner Metropolitan Council (a regional governmental agency and planning organization serving the seven-county metropolitan area) separated the Trout Brook Interceptor in the 1990s. It later transferred ownership to the CRWD in 2006.

"They had determined they no longer wanted to own stone sewer interceptors and were looking for an agency to take over its ownership," Eleria says. Because the interceptor serves an area of 8,000 acres (32,400m²), from more than one community, she explains, it made sense from a more regional entity to assume ownership.

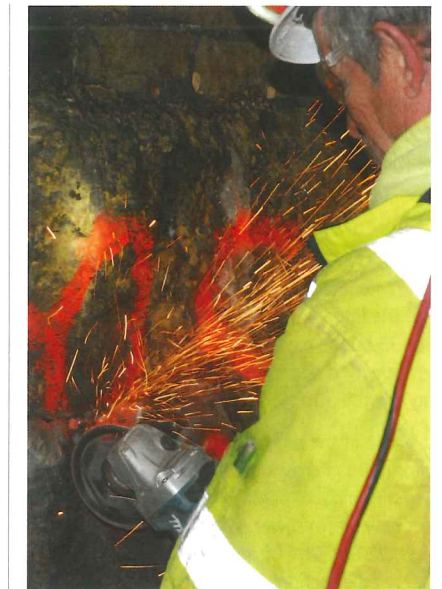
"It's not typical for a watershed district or water management organisation to own infrastructure like this."

CRWD is a special unit of government in charge of managing water resources within its designated boundaries. It relies on consultants for assistance in inspection, maintenance and repairing its tunnel system, and Barr Engineering has been in this role for about 10 years. The district inspects the tunnel on a five-year cycle and has developed a five-year capital improvement

Right: A 12-inch-thick, self-supporting shotcrete overlay built inside the historic tunnel



Above left: Damage to the limestone bricks



Above right: Grinding work on the tunnel's historic surface

plan to cover the cost of the repairs.

Only the original 2,500ft (762m) stretch of tunnel is built with limestone block. The rest of the interceptor is cast-in-place concrete and inspections show a majority of the tunnel is in fair condition. Joe Welna, an engineer with Barr Engineering, explains the work they've just completed is not in the worst rated section as far as the most recent (2014) inspection is concerned. Another section has a higher quantity of defects of higher severity. "We chose this section to start with because one of the defects in this limestone block tunnel was directly below a railroad track crossing with minimal cover."

The implications of a failure at this location would have many impacts. He explains, "with this limestone block tunnel we're counting on an arching effect of these blocks. During the inspection we found that several of the blocks in the keystone location had actually spalled out and split, and were in the invert of the tunnel."

The main objective of the project was to address the railroad crossing but to take advantage of the contractor mobilization Barr recommended additional repairs. One of the major ones was mortar repair, Welna says. He attributes the missing and deteriorated mortar to hydrogen sulfide from the tunnel's former existence as a CSO.



Left: Inspecting and marking the tunnel for repair work

"Typical defects had gaps in joints ranging from half an inch to 3 inches. In some sections the mortar was completely gone—it was overhead, on vertical surfaces."

The work is labour intensive—cleaning out damaged mortar and installing new mortar—and in some sections with high concentrations of damage it wasn't cost effective. Barr recommended a 2-inch-thick unreinforced shotcrete overlay for a 300ft- (91.5m-) long section of highly-concentrated mortar damage, and a 12-inch-thick reinforced shotcrete overlay at the railroad crossing. CRWD awarded a USD 1.2M contract to low bidder Minnesota-based Engineering & Construction Innovations, Inc. (ECI) in late summer 2016, with work starting from December 2016 through February.

TUNNEL WORK

Conveniently there is a parallel tunnel owned by the City of Saint Paul with a crossover upstream from the section where ECI would be performing the repair work, which allowed for the construction of a bulkhead and diversion of water for three months during the project.

"The base flow is year round, even in the winter, and typically 15 cubic feet per second (0.42 cubic metres), and that's basically just accumulation of infiltration from the entire system upstream, that's when the lakes are not discharging," says Barr Engineering's Nathan Campeau.

Working through the winter months meant fewer chances of a rainstorm—though an unusually warm February did cause the contractor to pull equipment a couple times.

For the sensitive area below the railroad crossing Barr evaluated a number

Recent repair work

2007–2009: As part of the transfer ownership from Met Council to CRWD, the District repaired two sections of pipe that were in poor condition. Due to severe cracking and settlement beneath the streets a 200ft (61m) settled or "sag" area of the 10ft (3m) diameter storm sewer pipe required a full replacement.

2012–2013: During the design phase of a nearby interstate reconstruction project the Minnesota Department of Transportation determined that a portion of the interceptor would have to be moved to avoid conflicts with Interstate-35 bridge piers. Constructed in two phases, the new Trout Brook alignment involved abandoning a 630ft (192m) section of existing pipe and replacing it with 830ft (253m) of new pipe in a nearby location.

The first phase of the project included building a new 160ft (48.7m) interceptor railroad crossing within a 30-hour work window and required shutdown of mainline railroad tracks. Afterwards, an additional 400ft (122m) section of new storm sewer pipes was installed. During the second phase of the project, 270ft (82m) of new pipe and the transition sections between the old and new pipe sections were constructed. Once the new alignment was online the old alignment was filled in or removed entirely.

of options even including realigning the tunnel. The main parameters were cost, structural integrity, longevity, coordination, overall repair difficulty, and hydraulic impact.

"We found that a 12-inch-thick overlay within that limestone block tunnel was probably the best option," Welna said. This new lining would be an approximately 200ft- (61m-) long section, and self supporting.

"Because a limestone block tunnel is somewhat hard to evaluate structurally—if you lose a block your structure is gone essentially—the 12-inch-thick overlay was designed as a stand alone structure so that the section of it is designed for the railroad loading. It doesn't count on any of the structural support of the limestone block tunnel."

The contractor prepped the surface with high pressure water to remove debris. The building process started with installing with the first of two mats of epoxy-coated rebar. Diameter in the tunnel can vary by ±6 inches on either dimension, Welna explains. He describes the overlay as a kind of composite structure with a cast in place 4ft- (1.2m-) tall wall or "knee wall." To seal the cold joint along the top, an expansive chemical grout water stop was injected, followed by the first shotcrete application along the arch.

"That's the beauty of shotcrete is you can kind of conform to the existing shape." Welna says. "If you were to try to use a form throughout this section you might be losing some hydraulic capacity."

After the first shotcrete lift was in place, ECI installed the second rebar mat

and the second, final shotcrete application. The spacing between the rebar is 8in.

Welna says the main challenge with this section was mitigating water infiltration, which they did with a combination of chemical grout and drilling what he describes as relief ports. These would redirect the water and after shotcreting around the ports they were plugged.

In the section of the tunnel with the high concentration of mortar damage ECI sprayed the 2-inch-thick overlay directly on the blocks. "With it not being reinforced we were really counting on a high performance mix to bond to the tunnel," Welna says. "It's not being mechanically held up there."

Barr Engineering chose a Sika prebagged mix with synthetic fibre reinforcement. Pull testing verified the application was getting a strong bond. "This was a pretty unique application because usually this material is used against concrete," he says. "This is a limestone block medium that we had to spray against."

The tunnel has encrustations on the limestone and part of the pull testing looked at whether the shotcrete could be applied directly or if it would need to be removed to get a good bond. The latter proved to be beneficial and the encrustations removed.

Mortar repair comprised roughly 5,700ft linear (1,737m)—it's basically tuck pointing, explains Welna. "First it was going and painting all the sections we wanted addressed. Then it was removing any unsettled material, removing the dust, the soil, the latency from any of these joints."

There was detail for mortar repair dry and mortar repair wet. "Some areas you actually had active infiltration water coming through. So we recommended that be sealed up prior to installation with chemical grouts."

PRESERVATION

Reflecting on the project Campeau highlights the district's motivation to restore the original workmanship, and appreciation of the tunnel's beauty and its historic nature—even though largely remains inaccessible to the public.

"Very early on CRWD decided it did not want to just automatically cover the entire tunnel and reline the whole thing. That was certainly an option, and certain areas definitely needed to be covered up because that was the safest thing to do structurally and the most cost effective thing to do."

Eleria responds, "we were really proud of the fact that we're taking responsibility for this storm sewer and highlight to the public the history of it—it's built over a century ago, in fairly good condition, we just need some repairs to make it last another 50-100 years more."

Below: Consultants measure damage in the tunnel



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STRENGTH MONITORING USING THERMAL IMAGING

In April Benoît Jones, managing director of Inbye Engineering and an Honorary Fellow at the University of Warwick, gave a presentation to the British Tunnelling Society Young Members on a new technology for monitoring the early strength of shotcrete called 'Strength Monitoring Using Thermal Imaging', or 'SMUTI'. This article is a summary of the presentation



Benoît Jones
Benoît is the managing director at Inbye Engineering

Acknowledgements

The author would like to thank Vishwajeet Ahuja, who conducted many of the tests shown in this paper while doing a PhD at the University of Warwick, Andy Male of Kandeo who was the software developer, the contractor at Bond Street Station Upgrade Costain Laing O'Rourke (CoLOR) JV and the client London Underground, the contractor at ARGE Tunnel Oberau Marti Tunnelbau and Inbye's agents in Germany Matrics Engineering.

THE MOST IMPORTANT THING to remember is that concrete strength gain is very temperature-dependent. If you cure concrete at 20°C instead of 10°C, the rate of strength gain doubles. If you go from 20°C to 30°C, it doubles again. And if you go from 30°C to 40°C, it doubles again, and so on. Therefore, concrete curing at 40°C will be gaining strength eight times faster than concrete curing at 10°C. This is because the hydration reactions between cement and water, which are what causes the strength gain, are exothermic: a little bit of energy (heat) is needed to make each reaction

happen, but then those reactions produce even more heat. The higher the temperature, the faster the rate of reaction. For a given concrete mix, this is the single most important variable.

The amount of hydration reactions that have taken place, as a proportion of the total possible reactions, can be quantified by a parameter called the "degree of hydration", which goes from 0 to 1. If we cure concrete at different constant temperatures, and then plot the rate of hydration against degree of hydration, we get a family of curves as shown in Figure 1, page 40.

Figure 1 shows that the rate of hydration approximately doubles every time the curing temperature increases by 10°C. It is virtually impossible for degree of hydration to reach 1, as even in very old concretes, there is still some unhydrated cement. Degree of hydration is a very useful parameter, and is a far better measure of maturity than age. All concrete properties, including compressive and tensile strength, stiffness, shrinkage and creep, correlate much better with degree of hydration than they do with age, particularly during the first few hours and days.

Compressive strength has been found to have a linear relationship with degree of hydration. An example of this relationship from tests at Bond Street Station Upgrade is shown in Figure 2.

Each concrete mix will have a unique linear relationship. Generally, stronger concretes have a steeper gradient. This linear relationship only applies during early age, perhaps up to a few days or approximately 0.6-0.7 degree of hydration.

Figure 1 also illustrates the kinetics of concrete hydration. The slow rate of hydration at the start is known as the 'dormant period'. After this there is a rapid increase in the rate of hydration, which slows towards a peak and then decreases. A maturity relationship that takes account of temperature sensitivity can be used to 'affine' these curves, in other words, to make them all line up over each other. Therefore the shape of these curves is a characteristic of the concrete mix and depends on the properties of the cement, the admixtures used, and also the influence of cement replacement materials such as micro silica or limestone powder.

Figure 2 also shows that a critical degree of hydration is required before strength gain begins, usually between 0.05 and 0.08. This means that between 5 and 8 per cent of cement hydration reactions are needed for an initial skeleton to form and further reactions contribute to strength gain.

The rate of hydration can be found using the Arrhenius equation:

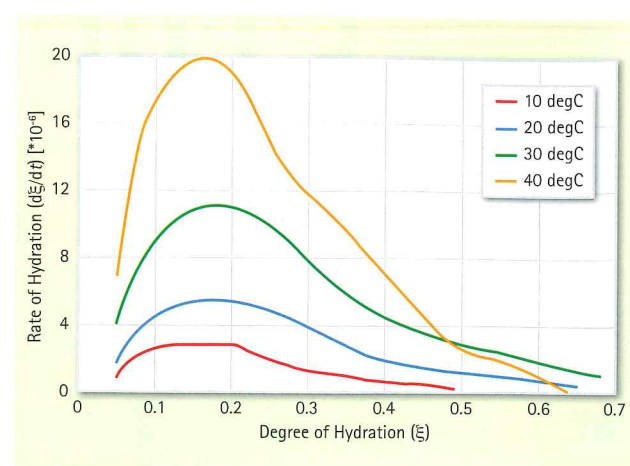
$$\frac{d\xi}{dt} = \tilde{A}(\xi) \exp\left(\frac{-E_a}{RT}\right)$$

where ξ is the degree of hydration, $d\xi/dt$ is the rate of hydration, $\tilde{A}(\xi)$ is the normalised affinity, E_a is the activation energy, R is the ideal gas constant and T is the temperature.

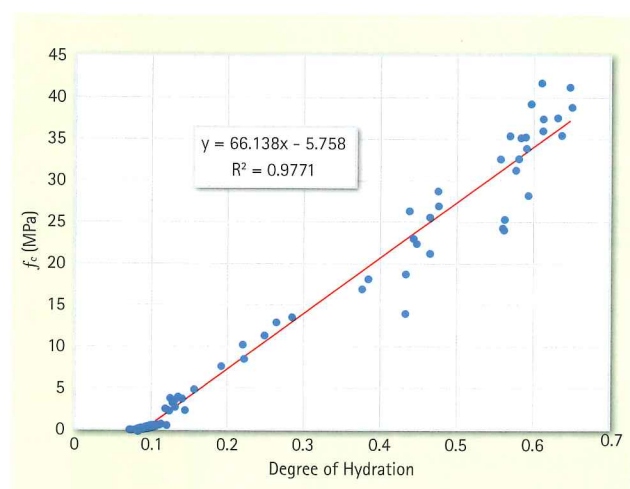
The normalised affinity is the shape of the affinity curves from Figure 1, which can be thought of as the signature of the concrete mix. It is a function of degree of hydration. It describes how easy it is for reactions to take place at different stages of hydration. When normalised affinity is high, it is easier for reactions to occur, and when it is low, it is more difficult. The normalised affinity is not temperature dependent.

An example of a normalised affinity curve for an accelerated shotcrete mix is shown in Figure 3. Note the difference from the shape of the curves in Figure 1, which is due to modelling the accelerator reaction. The accelerator causes a very high initial value of normalised affinity, making it very easy for reactions to occur. Then there is still a dormant period, followed by the long hump of the main silicate clinker reactions which is where most of the strength gain happens.

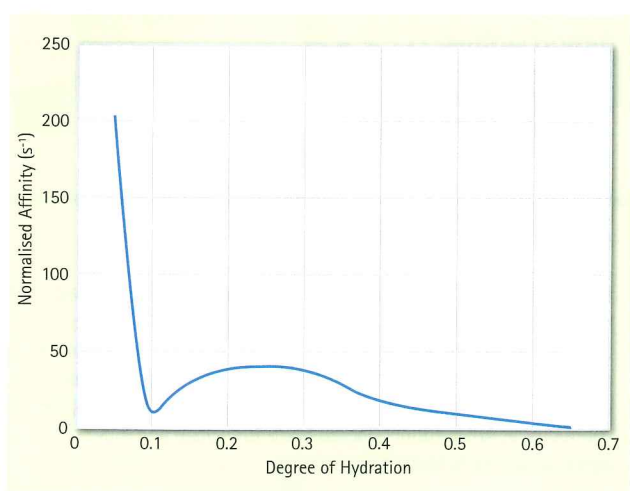
Right: Figure 1, Rate of hydration as a function of degree of hydration (tests by Vishwajeet Ahuja at the University of Warwick)



Right: Figure 2, Relationship between compressive strength (fc) and degree of hydration (tests performed on site by Vishwajeet Ahuja)

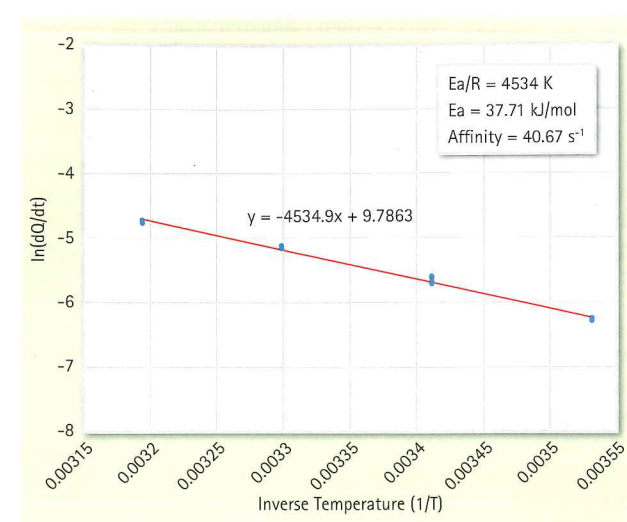


Right: Figure 3, Normalised affinity curve calculated from isothermal calorimetry for Bond Street Station Upgrade (based on tests by Vishwajeet Ahuja)

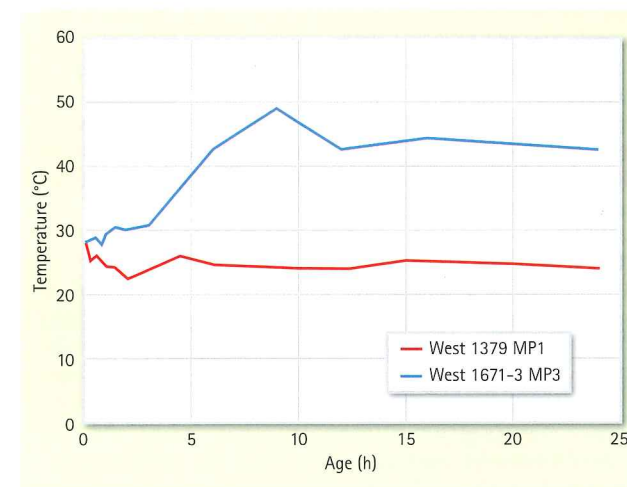


The activation energy can be thought of as the small amount of energy required to make each reaction happen. This is a constant and has units of Joules per Mole. This is the temperature sensitive part, and so it can be calculated from isothermal (constant temperature) tests at different temperatures. Figure 4 shows the activation energy calculation from Bond Street Station Upgrade. At each temperature, there are four tests, and the closeness of the points demonstrates the excellent repeatability of isothermal calorimetry.

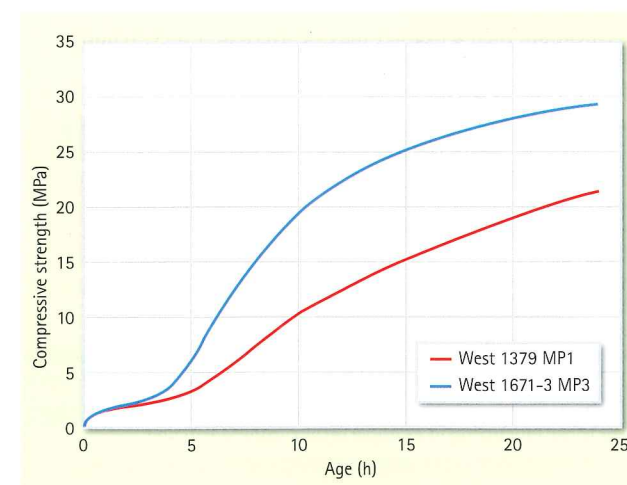
Using the Arrhenius equation means that at any time, the rate of hydration can be calculated if we know the current degree of



Left: Figure 4, Activation energy calculation for Bond Street Station Upgrade (based on tests by Vishwajeet Ahuja)



Left: Figure 5, Shotcrete temperatures measured at two different sections of the ARGE Tunnel Oberau, Germany



Left: Figure 6, Strength development calculated by SMUTI for the two temperature histories shown in Figure 5

hydration and the current temperature. Therefore, we can use a time-stepping algorithm to calculate rates and by integration over time, degrees of hydration, if we have the temperature history of the concrete.

STRENGTH TESTING AND MONITORING

Strength testing of concrete can be thought of as having two distinct purposes, which are often conflated:

- Testing for conformity – i.e., does the concrete delivered to

site have the properties we expect it to have, does it meet the specification? Often compressive strength is used as an index test (or 'identity test') to verify conformity of a whole range of properties on a day-to-day basis, such as flexural tensile strength, durability, etc., during construction.

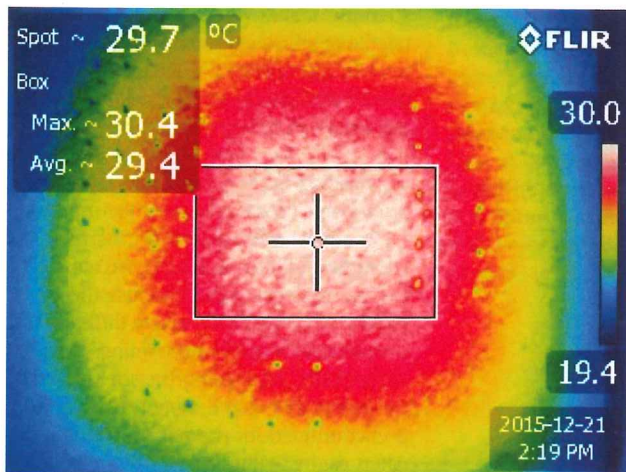
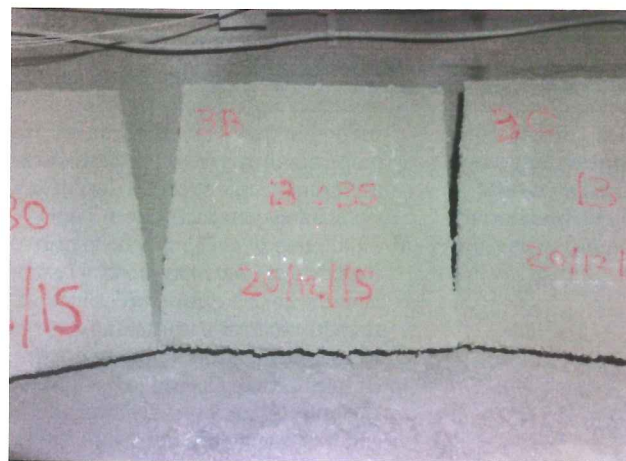
- Monitoring of strength development for safety of temporary works – i.e., does the concrete have sufficient strength to allow a shutter to be struck and falsework to be removed? Or for shotcrete, does it have sufficient strength to support its own weight and the ground loading?

In Europe, testing of early age strength of shotcrete is mainly done with needle penetrometer and stud driving tests to EN 14488-2: 2006. In the UK, due to concerns about the risk to operatives of falling shotcrete or ground near to the face, these tests are often performed on a test panel sprayed just after a section of lining has been sprayed.

In effect, when we are testing the strength of shotcrete panels, we are testing conformity. But because the panels may experience a very different temperature history to the lining, we are not actually monitoring the strength of the lining. This is the same problem that is encountered for normal concrete – when we test cubes or cylinders cured in a water bath at 20°C, is it representative of the concrete in the pour? In cold weather, this could lead to overestimating the strength of the concrete. For mass pours or in warmer weather, perhaps construction progress could be accelerated if we knew the actual strength of the concrete in situ.

A real example of measured shotcrete temperatures at different locations in the same tunnel is shown in Figure 5. Figure 6 shows the strength development calculated by SMUTI based on these temperature histories. In this case, the lower temperature was caused by groundwater inflow. A panel sprayed at the same time would not necessarily identify this disparity, which at 10 hours is approximately 10 MPa. The difference at very early age is not large, and this is because the fresh concrete temperatures were similar. On sites where the fresh concrete temperature may vary, significant retardation at very early age may be experienced, and this may not be evident in a panel sprayed after the lining, when the equipment and concrete have had a chance to warm up.

The converse of this is that SMUTI is not as direct a measure of conformity as strength testing. Although significant



Above: Figure 7, Digital and thermal images of shotcrete panels during calibration

deviations from expected temperature profiles would indicate a quality issue and intelligent triggers can be programmed into the software, the calculation assumes that the shotcrete delivered is the same shotcrete that has been tested in the laboratory, and that the only variable is temperature. Therefore, conformity has to be separately assured according to the requirements of EN 206-1: 2000.

USING SMUTI

SMUTI uses a thermal imaging camera to collect the temperature history of the shotcrete lining. The temperatures go into the software, and the timestepping algorithm calculates the degree of hydration, based on the normalised affinity and activation energy obtained from laboratory tests on the shotcrete mix.

In order to know the strength, the linear relationship between degree of hydration and strength is required. Since shotcrete needs to be sprayed under site conditions to obtain realistic strength results, panels are sprayed and simultaneously monitored for strength and temperature (Figure 7). The degree of

hydration found by SMUTI is then calibrated against the strength testing results. An example is shown in Figure 2. This linear relationship and the temperature history is used by the software to provide strength results in real time.

SMUTI is currently used on representative areas of the shotcrete lining for each advance. For instance, the left axis, left shoulder, crown, right shoulder, right axis is usually the default. Other areas of concern, perhaps identified by having a significantly different temperature to the rest of the lining, can be easily added into the software.

Currently, research and development is focussed on integrating SMUTI with photogrammetry or laser scanning, so that the temperature history of every point on the lining is known, every scan being positioned in 3D space. This would give the engineer a near-real-time 3D view of shotcrete thickness, age and compressive strength.

The software can work offline, and synchronises with a server database when connected, enabling the data to be viewed from anywhere in the world. It tracks which user has entered which data, and does not permanently delete anything, making it easy to undo any edit or delete errors.

The experiences gained on site so far indicate that using SMUTI is very quick and intuitive with engineers reporting no problems using it. The training, not just on how the software works, but also on the theoretical background, upsills the engineers and miners, increases motivation and ownership and improves safety, efficiency and quality.

CONCLUSIONS

SMUTI allows us to monitor the strength gain of the whole shotcrete lining (as against local tests on a panel that may not be representative) from a safe and remote position. There is no other method or technology that can achieve this; it represents a step-change in safety and quality control of shotcrete tunnelling.

Most in situ strength testing is *conformity testing*, and is not actually monitoring the safety of the temporary works. SMUTI monitors the early age strength of the shotcrete lining to allow better decision-making. If the actual strength is below the specification, then a disaster may be averted. If the strength is better than the specification, faster progress may be made without compromising safety.

SMUTI doesn't need to replace traditional strength testing to be beneficial. When it is used in parallel with existing methods, it provides increased confidence in the extrapolation of test panel strengths to the lining and helps engineers and operatives understand the strength development better.

The software is very easy to use and taking readings is very quick and easy. It provides rich, accessible and traceable data.

Further reading

For those interesting in example results from SMUTI and comparisons with other strength testing methods, they may be found in:

Jones, B. D., Davies, A. G. & Ahuja, V. (2017). Sprayed concrete strength monitoring using thermal imaging at Bond Street Station Upgrade. *Proceedings of the World Tunnel Congress – Surface Challenges – Underground Solutions*, Bergen, Norway. Norsk Forening for Fjellsprengningsteknikk (Norwegian Tunnelling Society).

Ahuja, V. & Jones, B. D. (2016). Non-destructive approach for shotcrete lining strength monitoring. *Proceedings of the World Tunnel Congress*, San Francisco, 22nd - 28th April 2016. Englewood, Colorado, USA: SME.

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Wuhan, China

Following the success of the first two TBM Digs events, the conference returns for the third time. This year it heads to the city of Wuhan in China's Hubei Province.

www.tbmdigs.org

12th Iranian Tunnelling Conference: Tunnelling and Climate Change

27-29 November 2017

Tehran, Iran

Drop in total precipitation around the world, especially in the Middle East and Iran has resulted in rapid decline of water resources. Water conveyance tunnels by transferring water from water-rich regions to arid regions can have a significant role in reducing consequences of this phenomenon. In some countries climate change has given rise to precipitation and has caused massive floods. In these countries drainage systems and water conveyance tunnels can have an important role in mitigating negative effects of flooding and climate change.

www.itc2017.ir

Stuva Expo 2017

6-7 December 2017

Stuttgart, Germany

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

www.stuva-expo.com/en/

2018

IFCEE 2018

6-10 March 2018

Orlando, Florida

The world's leading foundations congress and equipment expo will be a broad-based geotechnical/geoprofessional event with a focus on case histories, providing value to practitioners as well as academia.

www.geoinstitute.org/event/2018-geo-congress/

NASTT No Dig 2018

25-29 March 2018

Palm Springs, USA

Since 2001, this show has nearly doubled in size, keeping pace with the rapid growth of our industry. Cutting-edge technologies are continually being developed and introduced, see them at the largest trenchless technology show in North America.

www.nastt.org

World Tunnel Congress 2018

20-26 April 2018

Dubai, UAE

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

www.uaesocietyofengineers.com

North American Tunnelling Conference

24-27 June 2018

Washington D.C., USA

The NAT is the premier biannual tunneling event for North America, bringing together the brightest minds in the tunneling industry.

www.natconference.com

11th International Conference on Geosynthetics

16-21 September 2018

Seoul, South Korea

The technical program will include a Giroud lecture, 5-6 plenary lectures (special lectures), 2-3 short courses and approximately 50 parallel sessions. It is expected to attract more than 1,000 experts from over 100 countries.

www.11icg-seoul.org

PIARC International Conference on Road Tunnel Operations and Safety

3-5 October 2018

Lyon, France

This World Road Association endorsed event comes amidst increasing interest in the emergence of new types of vehicles in the driving environment, and how tunnels will keep pace with continuing technological advances.

www.piarc.org

10th Asian Rock Mechanics Symposium

29 October-3 November 2018

Singapore

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

www.arms10.org

2019

World Tunnel Congress 2019

3-9 May 2019

Naples, Italy

The one tunneling event that is unrivaled in its international reach. The World Tunnel Congress is coming to Italy and tunnellers representing owners, contractors, engineers and suppliers will be exhibiting. The event is expected to attract as many as 600 technical papers, 250 exhibitors and up to 3,000 attendees.

www.facebook.com/events/1753343481565751/

ECSMGE 2019

3-9 May 2019

Reykjavik, Iceland

The Icelandic Geotechnical Society are pleased to welcome you to the XVII European Conference on Soil Mechanics and Geotechnical Engineering, held in the Icelandic capital. The theme of the conference is "Geotechnical Engineering, foundation of the future" and will embrace all aspects of geotechnics.

www.ecsmge-2019.com

World Road Congress

6-10 October 2019

Abu Dhabi, UAE

The World Road Congress will cover a number of areas, including Road policies, Environment, Economics, financing, Governance of authorities, Planning, Risk management and many more.

www.piarcabudhabi2019.org

The British Tunnelling Society

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

BTSYM: Challenges in the drilling and blasting method at the main access tunnel for the Uma Oya Project

7 September 2017

The Uma Oya multipurpose project is a hydropower project in Sri Lanka with several tunnels over 25 km in length, mostly in hard rock. This presentation will describe some of the challenges and solutions in the Drilling and Blasting method used in this project during construction. Excavation of the underground powerhouse complex and associated tunnels will be explained and improvements in the drill and blast patterns implemented will be described.

Speakers: Mehdi Hosseini, London Bridge Associates

High Speed Railway Tunnel Projects & General Tunnelling Status in China

21 September 2017

This presentation will be given by the China Railway Tunnelling Group Contractors & China Railway Engineering Equipment Group. It will discuss the status of high speed rail technology in China with a particular emphasis on the design, construction techniques and use of TBMs in the tunnel sections of current major projects. An overview will be given of how the roles of client, designer and contractor operate in the Chinese market. The presentation will cover the past, present and future of high speed rail in China.

Speakers: Kung Wang and Yali Han

Finsbury Park Squareworks

16 November 2017

A presentation on the Finsbury Park Station step-free access scheme for London Underground. This will include information on squareworks tunnelling, shaft sinking and undertrack crossings, all carried out from within a live station.

Speakers: Farid Achha, London Underground; John Elliott, Alan Auld Engineering; Menelaos Lydakos, C Spencer Group

Waterview Tunnel, New Zealand

14 December 2017

The Waterview Connection in Auckland, New Zealand is the largest and most complex road project ever undertaken in New Zealand. The project involved two tunnels, each comprising three lanes, with an outside diameter of 14.41m excavated under residences, the Great North Road, and Auckland's western rail corridor.

Speakers: TBC

Tunnel Design Life of 120 years - Definition, Assessment and Improvement

18 January 2018

The first meeting of 2018 will focus on design life requirements of tunnels and how these are assessed by designers; and improvements and cost savings that can be made on projects when the concrete mixes are tested early on in the design stage.

Speakers: Charles Allen, Phil Bamforth, Jon Knights

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

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Tunnels & Tunnelling Subscriptions,
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reproduction in information storage and retrieval systems. Contact:
University of Microfilms International, 300 N. Zeeb Road, Ann Arbor,
Michigan 48106, US.

Tunnels & Tunnelling International ISSN (USPS 7330) 1369-3999 is
published monthly by World Market Intelligence, Progressive House, Foots
Cray, Sidcup, Kent, DA14 5HZ.

The US annual subscription price is \$283.49. Airfreight and mailing in the
USA by agent named Worldnet Shipping Inc., 156-15, 146th Avenue, 2nd
Floor, Jamaica, NY 11434, USA. Periodicals paid at Jamaica NY 11431.

US Postmaster: Send address changes to *Tunnels & Tunnelling
International*, Worldnet Shipping Inc., 156-15, 146th Avenue, 2nd Floor,
Jamaica, NY 11434, USA.

Subscription records are maintained at World Market Intelligence,
Progressive House, Foots Cray, Sidcup, Kent, DA14 5HZ.

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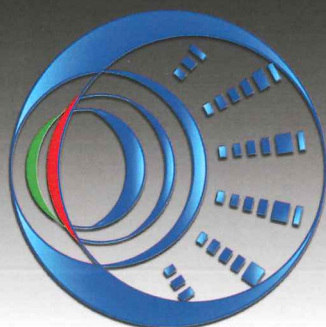
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