Every project has its own unique challenges, which is why every Robbins TBM is built with your specific needs in mind. Our relentless pursuit to innovate is driven by the needs our customers face every day. From machine design to tunnel completion, we are by your side working together to create new methods, and set new records in underground excavation.

We invite you to learn more about our latest products and projects in our 2017 presentation series at WTC and RETC.
SSE Generation Limited against Hochtief
The recent court findings attributing the burden of around £130M in rectification works of a brand new hydroelectric tunnel on the Client in a design and build contract has lessons and implications for the tunnelling industry in the United Kingdom and internationally, Professor Arnold Dix explains.

Tension at depth
Segmental concrete tunnel linings are evolving and no more so than in the demanding sector of deep sewers and outfalls. TJ spoke to engineers, contractors and suppliers to find out how.

Developing Delhi’s Metro
Eight Terratec Earth Pressure Balance TBMs successfully completed 20 drives on four major contracts for Phase III of the Delhi Metro, in India. With tunnelling now complete on this stage of the project, TJ takes a look back at the journey of these machines.

Blow-out failures part 2: purely cohesive soils
In part 2 of this article, Dr Benoit Jones of Inbye Engineering looks at blow-outs in tunnels in purely cohesive soils – what the critical mechanisms are and how they can be predicted.

A new standard for tunnelling contracts
A contractual standard specifically for the tunnelling industry is fast emerging on the horizon – the New FIDIC ‘Emerald’ Book. Ulrich Helm, Partner, and Fabian Bonke, an Associate, of the international law firm Hogan Lovells International LLP explain.

Automated design in practice
Ian Turner, Atkins tunnel engineer and software developer here describes a new framework for automated tunnel design.

D&B - new solutions for old problems
Increasingly high investment costs for a TBM are making companies look to alternatives, specifically drill and blast. Roger Murrow reports.

Product News
TJ rounds up some of the recent products made available to the tunnelling industry.

Contacts
DELHI METRO: 20 BREAKTHROUGHS SUCCESSFULLY COMPLETED

Eight TERRATEC Earth Pressure Balance TBM’s have finished their work on Phase III of the Delhi Metro, successfully completing a total of 20 drives on four major tunnelling contracts.

Each breakthrough occurred on schedule and within tolerance, demonstrating the reliability and accuracy of TERRATEC’s machines. In addition to supplying the TBM’s, TERRATEC provided comprehensive services on site to support the operation and maintenance of the equipment, assisting the contractors in their achievements.
Elon Reeve Musk, world-renowned entrepreneur, business magnate, investor, inventor, engineer, and all round good’n by all accounts, has entered the tunnelling business! On December 17th last year, infuriated whilst stuck in one of Los Angeles’ never ending traffic jams, Musk reportedly tweeted, “Am going to build a tunnel boring machine and just start digging...”

Since then he’s not rested on his laurels, in February he started work, apparently by digging a large diameter, 32m long tunnel on the grounds of his Space X premises in LA. Now this tunnel, like Musk’s involvement with the tunnelling industry may end up going nowhere, but let’s be positive, and assume it’s a long-term proposition and commitment. If so, this could quite simply be the best news our industry has ever had. Musk has the foresight, drive, will – and vitally the vast amounts of financing – needed to smash through many of the barriers that so severely hold us back.

Musk 100% believes that TBM advance rates can be hugely increased by pumping money into technology development - something we as an industry are so averse to doing - and Musk seems a man who won’t take ‘it can’t be done’ for an answer.

Lok Home spoke about it so succinctly in his recent Blog on the Robbins Company website, and apologies for such a heavy ‘lift’ but I couldn’t put it better myself: “Nearly all tunnels are heavily specified to avoid risk taking by owners (therefore discouraging new development),” Lok says, “Nearly all tunnels go to the low bidder and low bidders try to buy the TBMs at the lowest price; a further discouragement of development. The industry has therefore been slow to improve advance rates, but with Musk bringing the issue into the spotlight, perhaps things will change.”

Musk looks to be in an enviable position, one where he can take risk by the scruff of the neck and throw it down a very big hole, because he can afford to make the odd developmental mistake along the way - something the tunnelling industry most certainly can’t! Quite to the contrary, the innovators in our industry, and there are many, appear frustratingly tied into a straitjacket, padlocked by understandably risk-averse clients.

And therein, my hard hatted friends, lays the key, and why Musk entering the arena could be a momentous event for the future of the industry. On the horizon could be the creation of unprecedented levels of technology development with no attached risk taken on by current infrastructure, or to designer’s credibility and contractor’s futures, the list of positives is endless.

Interestingly - and this does tie in so bear with me - I recently attended a BTS Young Members Conference and the last session involved delegates being split into groups and asked to come up with their ‘dream list’ of things that could change the industry going forwards. One group, more from the Musk school of ‘outside the box’ thinking requested a nuclear powered TBM that could cut through anything! But, many put forward solutions required from the soft engineering side, better methods of information sharing, and also more clear-cut contract set-ups.

So, it’s almost beyond coincidence that on p48 of this very issue we have an exclusive article describing a potentially groundbreaking (excuse the pun) move by ITA and FIDIC, in the development of a FIDIC ‘Emerald Book’ (working title) specifically for the tunnelling industry. Space here prevents detail, so I suggest you read it for yourself, but combine the prospect of huge levels of technology development with the invention of a ‘one size fits all’ clear cut contract form for tunnelling, and it is very possible that in just a few years the tunnelling industry could progress decades. What exciting times to be a tunnelling engineer!

Tris Thomas
Preferred contractor chosen for Melbourne West Gate Tunnel Project

April 3, 2017

CIMIC Group company, CPB Contractors, has been selected by Melbourne’s Transurban as the preferred contractor to deliver Victoria’s multi-billion dollar West Gate Tunnel Project in a 50:50 joint venture with John Holland. The project includes building a 2.8km eastbound tunnel and 4km westbound tunnel under Yarraville.

As part of the agreement, the joint venture partners will now work with Transurban and the Victorian Government through an Environment Effects Statement (EES) process, which will assess the potential environmental, social, economic and planning impacts of the project, and recommend the approach to managing these impacts.

A comprehensive engagement program to seek input into the project from stakeholders and the community will be undertaken throughout the EES process, with a public exhibition period expected mid-2017.

Following successful completion of the planning process, revenue to CPB Contractors will be finalised at contract execution.

CH2M withdraw interest in HS2 Phase 2b

March 29, 2017

Jacqueline C. Hinman, Chairman and CEO of CH2M, has written to David Higgins, Chairman of the UK’s HS2 Ltd, to formally advise him of CH2M’s withdrawal of interest in the Phase 2b Development Partner Contract.

This follows continuing discussion between HS2 Ltd and CH2M with regard to the award of the contract. The resulting protracted delays and ongoing speculation risk further delays to this critical national infrastructure, thereby increasing costs to UK taxpayers, as well as to the firm.

CH2M remain fully committed to working with HS2 Ltd on delivering Phase 1 on time and within budget.

A spokesperson for CH2M said: “CH2M today provided formal notice to HS2 Ltd that we are withdrawing our interest in the HS2 Phase 2b contract.

“CH2M has demonstrated all appropriate measures taken throughout to ensure the integrity of the procurement process. Notwithstanding these efforts, we have taken the decision to alleviate any further delays to this critical national infrastructure project, which could ultimately lead to increasing costs to UK taxpayers, as well as to our firm.

“CH2M’s reputation reflects excellence earned by placing the interests of our clients and communities first, best exemplified by our delivery of vital programmes like Crossrail, the London 2012 Olympics, the most sustainable to-date; HS2 Phase 1; and the Thames Tideway and Lee Tunnels."

Laos breaks through ahead of schedule

March 27, 2017

On March 18, 2017, SELI Overseas broke through – using a TERRATEC 5.74m diameter H43 Double Shield TBM – into a reception chamber on the Xe-Pian Xe-Namnoy Hydroelectric Project, in southern Laos, successfully completing a 11.5km long drive for the project’s low-pressure headrace tunnel. The breakthrough came three and a half months ahead of schedule. Mucking out with rolling stock, SELI Overseas achieved impressive production rates with the powerful TBM during the course of the project – including a record-breaking single month advance of 1,005m in July 2016 – allowing the contractor to finish excavation ahead of schedule.

Fehmarnbelt technical consultancy contracts awarded

March 21, 2017

Femern A/S, client for the 18km long immersed tube tunnel across the Fehmarnbelt, has today signed contracts with Ramboll-Arup-TEC JV for the supply of technical client consultancy services and with ÅF – Hansen & Henneberg for the supply of in-house technical consultancy services. The tunnel will connect Rødbyhavn in Denmark with Puttgarden in Germany and will be the world’s longest immersed tunnel and the world’s longest road and rail tunnel under water.

Commenting on the two framework agreements, Technical Director Henrik Christensen, Femern A/S, said: “We have received strong and high calibre offers from the consultancy firms that took part in the two tenders. The appointment of the two
consortia underlines our confidence in the robustness of our technical platform to support our work on the current German approval process prior to the start of construction.

“When it comes to building the world’s longest immersed tunnel, quality should be “best in class” and we have no doubt that this is what our consultants will deliver. Their role will be to advise and challenge so that we achieve the best possible solutions. This, therefore, marks a very important day for the project. It’s now a question of when, not whether, construction gets underway. Everything is ready on the Danish side and we are doing all that we can to win German approval as soon as possible”.

**TfL announces Silvertown Tunnel shortlist**

**March 15, 2017**

Transport for London (TfL) has announced the three companies who have been shortlisted to design, finance, build and maintain the Silvertown Tunnel – a new twin-bore road tunnel proposed for east London. The bidders who have been shortlisted to design and build the tunnel are:

- Cintra Global Ltd
- Hochtief PPP Solutions GmbH
- Skanska Strabag

Construction of the new twin-bore road tunnel would begin in 2019, subject to final planning approval by Secretary of State. The tunnel would then open in 2023, helping to ease the current serious traffic congestion at Blackwall Tunnel and improving the reliability and resilience of the road network in east London. It will also enable significantly improved cross river public transport connections, with all buses using the tunnel being hybrid, electric or at least Euro VI when it opens.

**Hong Kong’s Immersed Tube milestone**

**March 14, 2017**

Hong Kong MTR’s Shatin to Central Link (SCL) has celebrated another milestone at the former Shek O Quarry with the completion of all the pre-cast units for the 1.7km long new cross-harbour railway tunnel.

The new tunnel section will extend the East Rail Line across the harbour to a new station in Wan Chai North and terminate at Admiralty.

Witnessed by government representatives and working partners, water started to flow into the basin where eleven tunnel units have been fabricated. In two months’ time, these pre-cast tunnel units will be floated and towed to the sea one by one for further immersion and connection on the seabed of the Victoria Harbour.

Mr TM Lee, General Manager – SCL and...
Head of E&M Construction of MTR Corporation said at the celebration today, "The water filling into the casting yard brings us a step closer to the delivery of the SCL cross-harbour tunnel. Our project team has geared up to prepare for the next challenge when the new cross-harbour tunnel units submerge under the Harbour which is targeted for completion by early 2019."

**CBE Group celebrates 30th Anniversary**
**March 13, 2017**
On the 13th of March 2017, CBE Group celebrated 30 years of activity within the tunnelling industry. To celebrate this anniversary, a group of employees will perform a 45km long relay race on the 17th March, from Ile Bouchard, its production site, to Saint-Avertin, headquarters of the company.

This race will be followed by a meal for all company employees, where Didier Lefebvre, CEO, will speak about the history of the company and its singular status, as a French SME which is successful worldwide. As part of the 30th anniversary, CBE Group will organize two other events, through the year, one for its agents and the other for its customers, during the AFTES convention (French Association of Tunnelling and Underground Space) in November 2017 in Paris.

**Sandvik and IBM join forces**
**March 3, 2017**
Sandvik Mining and Rock Technology today announced an agreement with IBM to jointly develop Data Driven Productivity and Predictive Maintenance services for the mining and rock excavation industry. Under the agreement, Sandvik and IBM will develop advanced analytics solutions to improve safety, maintenance, productivity and operational services of mining and rock excavation equipment.

The growth in onboard instrumentation and data gathering capabilities in heavy equipment are presenting natural resource industries with opportunities to employ advanced analytics and models to identify and resolve productivity issues and improve process optimization and performance. Deployment of digital technologies are expected to create as much as $100bn value to resource producing companies by 2035.

**Strabag replaces Hochtief in Austria following contract termination**
**March 2, 2017**
A Strabag AG/Jäger Bau GmbH/G. Hinteregger & Söhne Baugesellschaft m.b.H JV has assumed the tunnel driving works on Austria’s Maria Stein pressure flow tunnel on the Gemeinschaftskraftwerk Inn (GKI) power plant project. The move follows the recent termination of the original contract with Hochtief.

A GKI statement said, “This building contract was terminated by mutual agreement early on 14.02.2017. In the spring of 2017, the excavation work will be continued with a new contractor.”

The construction consortium has been hired to build the remaining 19km (of a total of 22km) of hard rock tunnel with a diameter of 6.5m. Two Robbins TBMs are in use on the project. The construction contract was concluded on the basis of an alliance and partnering model.

The power plant is scheduled for operation in 2020. When completed, the facility along the Swiss-Austrian border region will generate more than 400GWh of electricity and in doing so make a significant contribution to Tyrol’s energy autonomy.

The total investment in Gemeinschaftskraftwerk Inn GmbH – including the construction works – is estimated at €460M.

**Thai success for Terratec MTBMs**
**March 2, 2017**
In February 2017, TERRATEC Micro Tunnel Boring Machines (MTBMs) achieved several milestones on the Bangkok Metropolitan Electricity Authority’s (MEA) new cable tunnel system, in Thailand. At present, four Total Solution Pipe Jacking Systems are at work on two separate projects for the MEA’s 230kV ultra high-voltage underground cable tunnel programme, which is being undertaken to meet the ever-increasing demand for energy consumption in major business areas of the city. These include two DN1500+ Slurry MTBM Systems for the Italian-Thai Development Public Co. Ltd.’s (ITD) contract on the MRT Green Line (North) Cable Tunnel Project and two DN1800+ Slurry MTBMs that are being employed by Drill Tech (Thailand) Co., Ltd. on the Chaloomphrakiat RAMA IX Cable Tunnel (Srinakarin to On-nut section).

**HS2 gains Royal Assent**
**February 28, 2017**
The UK’s HS2 has taken a major step forward by successfully completing over 3 years of Parliamentary scrutiny to receive Royal Assent. Construction will now begin on schedule in the spring.

Transport Secretary Chris Grayling said: “Getting the go-ahead to start building HS2 is a massive boost to the UK’s future economic prosperity and a further clear signal that Britain is open for business.

“HS2 will be the world’s most advanced passenger railway and the backbone of our rail network. Royal Assent is a major step towards significantly increasing capacity on our congested railways for both passengers and freight; improving connections between the biggest cities and regions; generating jobs, skills and economic growth and helping build an economy that works for all.

“By investing in infrastructure the government is seizing the opportunity provided by leaving the EU to build a more global Britain. We will now press ahead with constructing the railway while continuing to ensure affected communities get appropriate support and are treated with fairness, compassion and respect.

**CREG “Golda” EPBM launched in Israel**
**February 28, 2017**
20th February saw the launch of the first of six CREG EPBMs to be used on the 23km Red Line for the Tel Aviv Metro in Israel. More than 300 guests, including Israel’s Minister of Transport and the Chinese Ambassador witnessed the event.

Tel Aviv is the second largest city in Israel. To reduce traffic congestion, Israel’s government is constructing seven light rail lines. The Red line is one of these seven, with a total length of 23km. Underground works are divided into a TBM driven section, a traditionally excavated section, and 23 stations. The six CREG EPBMs will work on the Red Line west section.

CREG’s “Golda” EPBM is 105m long with a diameter of 7.53m, and was launched at the Galei Gil shaft and with breakthrough scheduled at Ben Gurion station.
VERSATILITY & VISIBILITY
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With penetration rates up to 17 percent higher than its predecessors* and a new cabin that increases visibility by 25 percent while minimizing noise levels, the fully-automated Sandvik DT922i twin-boom jumbo is engineered to improve your tunneling operations. Developed for versatility, Sandvik DT922i excavates cross sections up to 125m², including face drilling, bolt-hole drilling and long-hole drilling. An intelligent, state-of-the-art control system and Sandvik iSURE® excavation management tool help ensure top tunneling quality.

*Test results and calculations are to be considered as results reached under certain and controlled test conditions. These test results and calculations should not be treated as specifications and Sandvik does not guarantee, warrant or represent the outcome of test results or calculations in any or all circumstances.
Tunnelling Journal issues arrived and all I can say is another resounding WOW! The Lake Mead article is by far my favorite of all of them written to date. Really brilliant…thank you Robin Rockey, Project Information Manager, Southern Nevada Water Authority

In my view Tunnelling Journal is the GO TO voice of the Global Tunnelling Industry. It provides concise and accurate updates with feedback and opinion when appropriate on all pertinent issues happening, in real terms today. Whether the focus is Project, Equipment or Company related I find the detail in both print and electronic format a must read.

Paul Bancroft, Product Director, Joy Global

It is always interesting and beneficial to read the latest issue of the Tunnelling Journal. The Journal provides current news and can be relied upon to update the reader on recent developments in the industry. The editors are not afraid to touch on some troublesome, if not controversial editorial topics, and we admire the sharp pen approach! The journal is an excellent voice in the interest of the industry in terms of featuring site reports from challenging projects, and taking active part and covering industry events and conferences. Your global coverage is an asset. Your team of writers and approach is an honest one and true to the industry, and from our stance, is one of the best promoters of the modern use of underground space. You have been a forerunner in the adoption of new media technologies such as with your updated web page, newsletters and webinars.

Tom Melbye, Senior Advisor, Normet International Ltd

Continuous progress underground is absolutely essential today for cities, nations, economies and finally the global community as a whole to prosper. The innovative players in global tunnelling have a decisive key competence of creating particularly sustainable values and assets by high-quality and high performance tunnel infrastructures. The premium magazine “Tunnelling Journal” not only certifies the engineering and operative progress in construction of underground structures. In print and online media, the editor-in-chief and his team also particularly present the fascinating professional diversity of our industry – with true journalistic demands and an impressively consistent quality.

Achim Kühn, Head of Group Marketing & Corporate Communications, Herrenknecht

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Paul Bancroft, Product Director, Joy Global

I STILL THINK YOU GUYS HAVE THE ONLY RAG WORTH TAKING TO THE LOO

Tyler Sandell, Sales Manager, The Robbins Company

Since its inception I have been an avid reader of, and occasional contributor to, Tunnelling Journal. Along with its web based news service it helps to keep our global community informed of the news and views from around the world. The standard of the technical articles and site reports is excellent and the team are never afraid to take on the current issues facing the industry. Tris’ editorials are always thought provoking with the added benefit of only leaving room for half his face on the page! Something we can all be thankful for.

David Salisbury, Secretary Hong Kong Tunnelling Society

TJ CONTINUES TO BE THE PREMIUM MAGAZINE FOR RELEVANT GLOBAL NEWS IN THE INDUSTRY.

The articles provide enough technical content to satisfy the hard core engineers without overloading the casual reader. The team at TJ are always approachable and their partnership with industry stakeholders is always fair and accommodating.

Matt Ross, Head of Underground Construction Chemicals, BASF Construction Chemicals
Visit our stand
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› RETC 2017 San Diego, US stand n° 503

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SSE Generation Limited
the £130M Collapse at Loch Ness

The recent findings of Lord Woolman attributing the burden of around £130M in rectification works of a brand new hydroelectric tunnel on the Client in a design and build contract has lessons and implications for the tunnelling industry in the United Kingdom and internationally.

The Court placed liability at the foot of the Client in a design and build context, even where the collapse occurred within a short period after commissioning. The way in which the Court dealt with expert evidence as well as legal principles and concepts provides a tangible insight into the management of risk during construction projects. This brief commentary, soley relies upon material disclosed in the Judgement of the Court case and is not the synthesis of 80,000 pages of evidence and argument. ( “[x]” in the text is a reference to the key paragraphs of the court case.)

By Professor Arnold Dix, Lawyer and Scientist, and CEO of the ALARP group of companies.

THE GLENDOE HYDROELECTRIC SCHEME suffered a catastrophic tunnel collapse shortly after being handed over to the Client. Its’ design life was 75 years and the collapse occurred during the commissioning period. The project reportedly enjoyed an excellent professional working relationship between the Client, its’ experts and the Contractors for the duration of the construction period. However, following handover, irregularities were detected within the performance of the hydro scheme ultimately resulting in it being switched off. The tunnels were then drained revealing an area of substantial collapse. Despite the prior excellent relations between the Client and the Contractors a dispute arose about payment for the remediation works and ultimately this resulted in another
contractor being employed to remediate the failed section of the tunnels.

**Design and rock classification**

A review of the Court documents reveals some interesting conclusions of fact. Firstly, and critically neither the Owner nor the Contractor’s experts noted any geological or geophysical defects during the tunnelling which demanded rock support in the area of collapse.

Both the “Q System” published by the Norwegian Technical Institute and the Contractor’s “Observational System” which relies on the skills and experience of the engineering geologist to assess rock mass of the tunnel were relied upon for rock mass classification. The tunnel was built using a TBM. It was contemplated that mostly the tunnel would be unlined, however the Court noted that:

“Most unlined tunnels require some support in section of weak rock and also close to the turbine.” [21]

The tunnel diameter was around 5m. The head race tunnel was around 6.2km long and the tail race tunnel was around 1.9km long spilling water into Loch Ness. It was agreed that the design life would be 75 years.

“Although I hold that the collapse was an employer’s risk event, I also conclude that any loss suffered by Hochtief was caused by its own breach of the repairing obligation...”
The parties
Interesting about the Glendoe scenario is that the case involves sophisticated contractors, clients and consultants from the mature tunnelling industry. The client, Scottish & Southern Electricity Group (SSE), is no stranger to hydroelectric schemes. Hochtief is one of the most highly regarded contractors in the world, Jacobs (Jacobs Gibb Ltd and Jacobs UK Ltd, together here as Jacobs) as the clients engineering geology consultant and supervisor, Pöyry Energy as specialist designer for Hochtief, and Andritz mechanical and electrical sub-contractor for Hochtief with extensive experience in hydroelectric power station refurbishment. Clearly this was a “top shelf” group with an equally impressive array of teams and individual experts supporting the project. In this context a catastrophic collapse of the tunnel is worthy of particular attention and the courts deliberations of the evidence presented by Senior Counsel (Queens Counsel in Scotland) means the readers can have confidence that this is a case which has been dealt with in detail, professionally and that the lessons to be gained should be considered carefully.

Geological context
The Glendoe Scheme required the construction of the head race tunnel through the Conagleann Fault Zone (“CFZ”). This zone was identified from the outset as posing a risk to tunnel integrity. A noted by Lord Wolman:

“While it is apparent on the surface the only means of knowing how the individual fault strands align and intersect with each other underground is to drill bore holes.” [37]

Legal Context - Tender Procedure
During the tender phase SSE told contractors that:

“Jacobs expected 97.5% of the excavation to be in “good” rock, but added that there was a plausibility about the ground conditions…” [37]

Hochtief submitted its tender stating that:

“During construction the support requirement will be decided at the face, based on actual conditions …” [38]

Prior to submitting its tender Hochtief asked SSE to drill a deep bore hole to find out more about the geology of the CFZ. His Honour found that that request was not fulfilled because:

“It would have required the largest drilling rig in the UK. At that stage there was no access road to allow such a rig to be transported by lorry. No civilian helicopter could lift a rig of that size.”

Jacobs prior to tender produced a ground reference conditions report based upon a bore hole examining where it was thought the CFZ intersected the tunnel. Subsequent to the collapse it was determined that this borehole missed the main area of the CFZ. As a result of missing the main area of the CFZ the parties were misled into thinking there were good tunnelling conditions in the CFZ.

Hochtief’s method relied on a TBM and initially expected to have only 40% of the head race tunnel lined. The contract price was £126M.

Culture during construction
The Court notes at paragraph 44 (the evidence of Hochtief) that from the outset of this project there was a good relationship between SSE (the Client), Hochtief, Jacobs, Pöyry, and Andritz. The Court noted the parties held weekly and monthly meetings to discuss technical issues, which they mainly resolved by agreement. A fact of specific reference is made to the culture of the project and this positive professional attitude onsite is testament to the high calibre of all parties in this case. Indeed the Court case as reflected in Lord Wolman’s judgement also reflects the high level of satisfaction of Lord Wolman with the clients in Court (albeit there are some criticisms in detail about the complexity, mass of documents and expert evidence preparation).

The TBM was of a gripper type and there was a probe drilling rig on the TBM. Because the conditions were so dry and there were no gas issues, forward probing was not required by Hochtief. From the TBM excavation perspective the conditions were very dry and there were few sections of weak rock.

Rock classes and mapping
Between the parties experts it was agreed that there would be only 4 classes of rock. Class 1 requiring minimal support; Class 2 involving rock bolts and shotcrete around part of the crown; Class 3 was full circumference shotcrete; and Class 4 prescribe increased shotcrete together with steel arches.

There was also the opportunity for the engineering geologists to specify additional support measure within a class on an as needs basis. [paragraph 53]

Both SSE and Hochtief employed geologists’ onsite to continuously agree on rock classification. Lord Woolman noted that the records reflected the fact that the
Winner of the Project of the Year Award (SPMI PoY) 2016-2017 in Engineering & Construction Category:
CREG Rectangular TBM for Trenchless Underpass at TEL T221 Havelock Station

CREG Double Shield TBM CREG 241 passed 6km drive for Lanzhou Water Source Project on March 9th 2017

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  41812, Erkelenz
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Website: www.crectbm.com
mapping procedure was conducted jointly and a draft rock excavation classification sheet was prepared with comments from all parties. Lord Woolman also noted that the practice was that Hochtief created a geological database and that as the database was updated an email would be sent to Poyry and Jacobs in the following terms:

“The latest rock excavation classification assessment and geological mapping can be found via the following link…. Please advise if the classification or support specification is at variance of your observations or design assumptions.” [63]

The Lord found that there was:

“… no evidence that anyone sought to change or otherwise queried the decisions being made onsite.”

Neither Poyry nor Jacobs took issue with the classifications being made. Furthermore Hochtief, Jacobs and Poyry all signed the rec sheets with the Client’s expert signing them “approved”. His Lord specifically notes that the signing of the rec sheets was “approved” and not “as seen” or “acknowledged”. His Lord also noted that:

The Client’s signature “approved” was included “many weeks later, he had ample opportunity to cross check classification … against the findings of the Q-System”.

Such a system demonstrates a high level of expertise, professional conduct and confidence in the process. It is further evidence of a sophisticated and mature system for construction on this project and this conclusion is reflected in the tone of the decisions by His Lord.

**Predicted and reality - The Rock Conditions**

The tunnel conditions actually encountered were much better than predicted. [67]

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<th>Expected %</th>
<th>As Built %</th>
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<td>Class 4</td>
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From this summary it is clearly apparent that the Client received the benefit of significantly better rock conditions and the Contractor was required to do significantly less remediation and structural hardening works than initially anticipated. The client got a lower price, the scheme was cheaper.

The article author - Professor Arnold Dix

**The Conagleann Fault Zone**

Hochtief was aware of the risks proceeding with the TBM through the fault zone and removed the probe rig in favour of enhancing the ability to install rock bolts and metal arch supports. Warnings were issued to mining personnel about the risk of travelling through the fault zone. This was expressed bluntly, warning TBM crews to take “extreme care” when walking through the area of the tunnel. Other warnings recorded by His Lord include:

“You are now in an anticipated fault zone so expect deterioration at any time.” [70]

**Observation** - There was no indication of poor rock condition in the CFZ. All documentation recorded that the conditions were Class 1. As noted by His Lord:

“The TBM has now passed through the predicted zone of the Conagleann Fault but indications of its existence were imperceptible.” [71]

After the completion of the tunnel, joint inspections took place. These inspections were attended by representatives of Hochtief, Jacobs and Poyry and there were only comparatively minor areas identified where strips of shotcrete and mesh were prescribed for very small areas of erodible rock. Tests were conducted in areas identified by Poyry to check for swelling clay minerals, but no potential problem was identified.

**At the Handover** - His Lord found that other than some small matters:

“No one expressed any concerns about the stability of the tunnels.

**Employer Takeover**

SSE issued a Takeover Certificate to Hochtief stating:

“… I confirm that I am satisfied that the power station and associated tunnels is now sufficiently complete for operation and is taken over by employer … The employer also takes over the head raise and tail raise tunnels …” [79]

There was a two year defects period and it was anticipated that there would be an inspection 2 years later to carry out defect inspections. Within a few months of opening odd measurements were being received on the head pressure in the system. There were no alarms but some of the indicated pressures and resultant hydroelectric generation were lower than expected. Over the next few months there were issued in the head reading and the scheme took an unusual amount of time to get up to a reasonable generating capacity.

**Relationships deteriorate**

Once it was decided to investigate the failings in the hydro scheme the relationships between the parties began to deteriorate; most importantly between Hochtief and the Client. Hochtief formed the view that they were being prevented from carrying out remedial works and the Client formed the view that Hochtief did not want to do the works. As one would expect it was a significant dispute over who should pay for them. As His Lord noted the question of who pays for it is a different point to who should actually perform the works. The initial response was that Hochtief did not accept liability but that it was preparing to mobilise. Various inspections took place, the debris pile identified was substantial almost totally constricting the tunnel, there were reports of vibration and the sounds of rocks fall occurring while inspections were being conducted.

Hochtief maintained the collapse was an employer's risk event and SSE asserted it was a contractor’s risk event. These views existed through to the Court hearings.

In the time that followed the detection of the complete collapse there was an impasse. Initially discussions were good but later they deteriorated rapidly. The exchanges became contractual in nature with SSE wanting the recovery project to initiate as soon as possible and Hochtief insisting detailed investigations should take place. There was also growing mistrust between the parties over the nature and extent of the collapse area as initially indications were that it was 270m long but later was thought to be more in the order of 100m long and this was not conveyed to Hochtief for many months.

This meant that when meetings occurred around a year later with suggestions of 50/50 costs sharing no agreement could be reached. Hochtief proposed that both parties and their insurers should nominate an expert panel of engineers to investigate the issue prior to
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implementing the fix. SSE was concerned that such a panel was not contemplated under the contract and that it would lead to a stalemate. Hochtief insisted it was an employer’s risk event because the Completion Certificate had been issued.

Parties relationship becomes dysfunctional
Following the collapse relationships degenerated rapidly. Hochtief’s view was that as the project had been handed over this was the Client’s risk financially and that a solution should be found after performing a careful analysis. On the other hand, the Client’s view was that Hochtief had failed to deliver the project correctly and that therefore they were required to fix it. The result was an impasse resulting in litigation, which took many years and cost countless millions of dollars in fees and wasted effort.

Mistrust grows
Around a year after the collapse the Health and Safety Executive (“HSE”) attended the tunnel, conducting an inspection and provided an advice on a mediation strategy. As noted by His Lord:

“As a result of a misunderstanding Hochtief was not present at the HSE meeting. SSE believed Hochtief thought it premature to discuss the repair works with HSE. In fact Hochtief had been willing to discuss the investigation works.”

His Lord singled out this event as substantially influencing the attitude of each party towards each other. As noted by His Lord:

“...it reinforced SSE’s view that Hochtief was not committed to finding an expeditious solution. It underscored Hochtief’s view that it was being excluded from the recovery project”.

His Lord found that SSE had a preference for Hochtief performing the remediation because of its knowledge and expertise of the site but that it was frustrated at the staff and resources made available. On the other hand, Hochtief was concerned that the necessary technical investigations were not being conducted in order to de-risk the remediation engineering and that it was being treated poorly by SSE.

Hochtief made various proposals such as a 50/50 cost sharing of a technical investigation and repeatedly reiterated its willingness to mobilise to site if paid to do so.

Around 13 months later SSE issued, what His Lord described as, “an ultimatum letter”. It demanded Hochtief provide a program of the remedial works within 14 days and agree to a 50/50 cost sharing until liability had been determined. Hochtief refused to comply with conditions, denied it had failed to make progress and suggested a further meeting as a matter of urgency. There was no further meeting.

Jacobs
Jacobs produced an outline of the investigations it thought were necessary for the remedial works including surface mapping, aerial photography, seismic topography and drilling of bore holes at specific locations.

The British Geological Survey (“BGS”) became involved in the matter, ultimately taking over four years to complete a fresh geological map of the CFZ. Ultimately the BGS concluded that:

a. “The CFZ is a complex fault structure with multiple zones of fractured rock over a short distance
b. It intersects the HRT at the collapse zone
c. The nature of the rocks in the collapse area is unknown” [135]

Findings – why did the tunnel collapse?
Hochtief provided two findings as a matter of fact as to why the tunnel collapsed.

The first one at paragraph [147] was because there was not enough support, poor rock conditions coincided with insufficient shotcrete and rock bolts.

More detailed findings of His Lord were that the great difficulty in providing a long answer as there has never actually been a full investigation of the cause of the collapse. The reason for this is that once it was decided to build a bypass tunnel the exact reasons for the actual collapse are academic, not really relevant, because the legal focus then turns to the construction of the bypass tunnel.

His Lord notes that the dimensions in the void range from 2,374 cubic metres to 13,000 cubic metres.

In the end His Lord was of the view that it was impossible to determine the cause of the collapse. His Lord was ultimately of the view:

“... The most likely explanation, which is neutral on the question of fault, is as follows:

1. The CFZ consists of interconnected faults of thin single shears with good rock in between.
2. The weak rock deteriorated and lost its strength when submerged, a process referred to as slacking.
3. The flowing waters washed out the areas of erodible rock.
4. The erosion progressed and opened up larger seams.
5. The erodible material was progressively deposited as sediment over a significant length of the HRT.
6. The HRT lost stability and the tunnel collapsed.
7. Dewatering caused further erosion.” [152]

The legal dispute
Under the terms of the contract the Client assumes risks for events which include:

“Loss of or damage to the parts of works taken over by the employer, except loss or damage occurring before the issue of the Defects Certificate which is due to ... a defect which existed at takeover …”

and

“a part of the works which is not in accordance with the works information or a part of the works designed by the Contractor which is not in accordance with the applicable law or the Contractors design which has been accepted by the Project Manager.”

The Client contended that both of the above limbs were satisfied and therefore the scheme could not:

“... provide reliable service without requirement for major refurbishment or significant capital expenditure”

because Hochtief failed to install the level of support to prevent the erosion of erodible rock during operation.

On the other hand Hochtief argued that:
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“The Contractor is not liable to defects of the works due to his design so far as he proves that he used reasonable skill and care to ensure that it complied with the works information.” [161and 162]

His Lord found that Hochtief did not guarantee the works. Instead Hochtief promised to build the works with “reasonable skill and care”. As noted by His Lord:

“Hochtief’s assumption of a more limited degree of risk would have been reflected in the contract price and the level of the insurance premiums.”

This is a very important distinction between what the Client thought they were obtaining and what Hochtief contractually agreed to provide. This meant that Hochtief could provide a lower cost to the Client.

His Lord rejected the proposition that the support scheme required Hochtief to shotcrete all erodible rock as outlined as the terms in the tunnel support methodology. He rejected the proposition that it should have installed Class 3 or Class 4 support wherever it found erodible rock. [165]

The reason His Lord rejected this approach are outlined in Clause 166 of the determination.

a. The overwhelming body of contractual provisions calling for the exercise of engineering judgement in the tunnel
b. The term erodible rock is vague and required interpretation at the face
c. It was not intended by the parties that a mechanistic process be adopted that responded without engineering judgement and care
d. The price would have been much higher for the Client if this was the criteria actually used
e. It would mean that it wasn’t possible to have an unlined tunnel in simple geology and yet it was the unlined tunnel which provided the enormous incentive for this economic construction
f. The provisions sought to be relied upon by the Client were actually designed to deal with water outflow and loss, not the issue of tunnel stability [166]

His Lord therefore concluded that:

“…the parties clearly agreed the approach had been taken about rock classification and support. The engineering geologists should jointly determine both matters within the tunnel. This collaborative approach had made great utility. It took advantage of the experience of all involved.”

Further the Court noted:

“it was beneficial for all parties for the classification of the ground to be checked as it went along because the consequences of defects being raised at a later date would create difficulties for both parties”. [171]

Critically and fundamentally and commercially of great relevance is the fact that this system meant that SSE: “only paid for necessary support”.

Joint inspections
It was important to His Lord to note that many experienced tunnellers scrutinised the HRT both during and after the TBM drive. They included engineering geologists, tunnel designers, engineering and TBM crews. They were actively looking for problems. None of them saw signs of fault that might threaten tunnel stability. None recommended the installation of a high level of support at particular locations. [180]

Prior to the tunnel going into operation Hochtief, Poynt, Jacobs and SSE inspected the whole tunnel on a metre by metre basis. Only minor issues were identified and these were resolved prior to water testing. His Lord noted with approval a report by what he described as a “distinguished tunneller”, there is no recorded evidence of passing through any feature that would potentially cause the catastrophic collapse that has occurred. [181]

His Lord holds that:

“A different classification system would not have resulted in the installation of heavier support”.

His Lord noted with approval that eminent experts stated:

“No system could have predicted the correct level of support.” [185]

His Honour put great weight on the fact that Jacobs had approved the rec sheets on behalf of the Client and that the collaborative approach had been taken about rock conditions encountered at the rock face.

On this basis His Lord found that Hochtief did exercise reasonable skill and care. As noted by His Lord the Client’s propositions are “founded on hindsight”. [187]

Hindsight is not, and can never be, the criteria for a determination of a liability. This case clearly supports the underlying fundamental proposition of legal systems in all jurisdictions (not merely common law jurisdictions) that hindsight is not, cannot and never should be the basis for determining liability in a case.

Should Hochtief have returned to site? Under the contract Hochtief was required to return to site. As noted by His Lord the contract provided that:

“Until the Defects Certificate has been issued and unless otherwise instructed by the Project Manager the Contractor promptly replaces loss of and repairs damage to the works, plant and materials.”

In these circumstances His Lord drew a distinction between a requirement to return to the site and perform the remediation and secondly whom is to pay for it. For these reasons a Court held that:

“… Wrangles about liability are postponed. If the damage is ultimately found to be to be an employer’s risk event, the contractor is entitled to payment. The repair works will be a compensation event: … If, however, the damage is due to a contractor’s risk event then it must bear the costs.”

Therefore His Lord found that Hochtief breached its obligations under the contract by linking an agreement to perform the remedial works to an agreement for payment.

Furthermore the Court held that as the collapse was an employer’s risk event, the employer has to bear the cost of the recovery project because Hochtief failed to perform the remediation (because it was demanding an agreement for payment) it cannot sue the Client for breach. [191]
The Court found that the client did not contribute to the damage by not recognising the unusual pressure measurement and loss of generating capacity as evidence of a catastrophic failure earlier. Therefore the Court held that there was no contributory negligence.

The Court found that the costs of the remediation were reasonable. The general principle which is applied is one founded in common law almost 100 years ago in Banco de Portugal v Waterlow & Sons Ltd 1932 AC 452, Lord MacMillan stated:

“It is often easy after an emergency has passed to criticise the steps which have been taken to meet it, but such criticism does not come well from those who themselves created the emergency. The law is satisfied if the party placed in a difficult situation by reason of the breach of a duty owed to him has acted reasonably in the adoption of remedial measures, and he will not be held disentitled to recover the cost of such measures merely because the party in breach can suggest that other measures less burdensome to him might have been taken.”

The fact that His Lord found that Hochtief refused to perform the remediation measures unless SSE agreed to pay the costs therefore placed a high barrier in front of Hochtief in order to prove that the damages claimed were unreasonable. His Lord finding that it was reasonable and that the costs were reasonable and he took note of the fact that cost auditors were involved in ensuring that the remediated works were correctly costed.

His Lord was particularly impressed by the costs monitoring that took place and that the scrutiny afforded by Gardiner and Theobald as cost consultants provided an appropriate level of scrutiny so therefore the costs were reasonable.

“[251] Although I hold that the collapse was an employer’s risk event, I also conclude that any loss suffered by Hochtief was caused by its own breach of the repairing obligation…”

Conclusions
This case provides potential wisdom and lessons on so many levels.

The key lessons are clear:
1. Despite the best endeavours of highly experienced contracting parties, ground conditions can and do conspire to cause catastrophic failures
2. Where clients seek to reduce costs as far as reasonably practicable and manage risks dynamically through such methods as agreed face mapping and risk assessment, to reduce costs, the burden of the lower cost can fall with the client.
3. Where contracts are entered into that do not impose absolute liability on the contractor, discharging due care and diligence is a defence to claims of liability against the contractor
4. Where obligations exist under a contract to rectify faults and the question of costs for those rectification works is at large, it is a dangerous strategic move to try and couple performing the remediation works to the payment for those works
5. It is essential in the event of a dispute that professional relationships be maintained wherever possible

The benefits of an impeccable working relationship between the parties, during the construction of this project, were entirely lost through a series of misunderstandings between the parties following the detection of the catastrophic failure in the tunnel. Respective blame for collapse can never be the basis for liability.

Had the parties taken up early offers of commercial settlement from the builder, or perhaps an expert dispute settlement process as suggested by the client, it is almost certain the case would have settled long ago without the public airing of the dispute and the huge time and financial costs.
Tension at DEPTH

Segmental concrete tunnel linings are evolving and no more so than in the demanding sector of deep sewers and outfalls. We spoke to engineers, contractors and suppliers to find out how. By Kristina Smith.

The Contractor who wins the contract for Los Angeles’ Joint Water Pollution Control Plant (JWPCP) Effluent Outfall Tunnel project will have an extra hurdle to clear when it comes to segment installation: half of the tunnel’s 11km (7 mile) length will require the tunnel’s rings to be post-tensioned.

Full-scale trials have confirmed that this is a good solution for the tunnel, which will from time to time experience a greater internal than external pressure. “The tests show that the concept of post-tensioning a segmented liner to create a ‘monolithic’ liner to prevent leakage into the surrounding ground works,” says Jon Kaneshiro, technology leader for tunnels at Parsons. “This avoids the need for a two-pass liner via installation of a pipe and backfilling the annular space.” Parsons worked with McMillen-Jacobs Associates, V&A Consulting Engineers and Precast Management Corporation (PMC) to carry out the tests for the Sanitation Districts of Los Angeles County. Eight contractors have submitted pre-qualification documents and the Sanitation District plans to send out tender documents in the second half of this year.

All over the world, authorities are creating large-capacity sewers to cope with growing urban populations and to relieve or replace sewage systems that are over-loaded and often over-flowing into rivers, lakes and seas. Often these programmes mean that several smaller pumping stations or treatment plants can be replaced by single, larger facilities freeing up precious space on the surface.

Current projects include Tideway in London, Phase II of Singapore’s Deep Tunnel Sewage System (DTSS), Ohio’s Project Clean Lake, Abu Dhabi’s Strategic Tunnel Enhancement Programme (STEP) and Dubai DS233 Deep Tunnel Storm Water System. These tunnels are often built at depth, not only to avoid existing infrastructure in the ground but to make use of gravity as they collect surrounding combined sewer outfall (CSO) flows.

Designers are faced with challenges and choices in selecting the optimal lining design. Like the JWPCP outfall tunnel, many must cope with both compression and tension forces due to surge events. And with design lives only getting longer, ensuring durability is vital; linings must withstand abrasion and corrosion due to the presence of substances including hydrogen sulphide.

The solutions vary, depending on ground conditions, local practice and the client’s appetite for risk. They include, one-pass linings, post-tensioned linings as already referenced, secondary cast-in-situ concrete linings, some with HDPE liners and the more traditional approach of a steel secondary lining. Newer solutions include segments.
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with HDPE cast into them and even – under consideration for Tideway – a segmental secondary as well as primary lining.

**Post-tensioning**

Though post-tensioned segments are by-no-means commonplace, it is a method with a history. Kaneshiro references projects in 1949 in France and 1960 in Germany for tunnels that passed under the Seine and Rhine, respectively.

“Design measures to keep liners in compression using modern tunnelling construction techniques were used for at least seven tunnels including San Diego’s South Bay Ocean Outfall in 1995, at least five tunnels in the late 1990’s in Japan, and most recently in Switzerland for the Thun tunnel in 2006. Five of these seven tunnels used post tensioning methods,” says Kaneshiro. “As the tunnel becomes larger, passive systems to confine the segments becomes less economical or impractical. Post tensioning becomes the economical and practical choice.”

The post-tensioning system for JWPCP consists of two 65mm (2.5inch) tendon ducts, each carrying four 15mm (0.6 inch) strands. PMC constructed and tested four rings at its yard in Las Vegas, using modified forms from San Francisco’s Central Subway Project.

Stacked four high with bulkheads at the top and bottom, the conventionally reinforced rings were 1.5m (5ft) long and 5.4m (17’10”) in diameter and 300mm (12inches) thick. Gauges on the segment joints measured displacements.

“The tests show that the concept works for the internal design pressures of 25.4 psi for the peak dry weather flow and 41.4 psi for the peak wet weather flows which are the net pressures over the ambient groundwater pressure,” says Kaneshiro. “The peak dry weather flow only occurs for about 10% of the operation time per year and the peak wet weather flow only occurs for less than 1% of the time. These are the expected peak events well into the future, beyond the 100 year plus design life of the project.”

**“Pre-stressing would increase resistance to internal pressures as well. This system could work very well structurally in tunnels with squeezing rock or tunnels with high seismic loadings.”**

Kaneshiro flags up corrosion protection as one concern for the design of the JWPCP Effluent Outlet Tunnel, although he adds that corrosion will be limited in a pressurised outfall because the effluent has been treated.
and there is no access to oxygen.

The solution for the JWPCP project is to use double corrosion protection systems from the pre-stressing and post-tensioning industry: corrugated plastic sleeves embedded in the concrete, grout inside the sleeve surrounding the tendon, and where the tendons are not grouted, the free tensioning length is surrounded by grease and the plastic sheathing and plastic anchor head cover.

Precast secondary lining

The Tideway Tunnel, which has been let in three sections, is the second phase of Thames Water’s programme to prevent raw sewage flowing into the River Thames and its tributaries during certain rainfall events. The first phase was the Lee Tunnel which is already in use, storing excess water until it can be treated.

The lining for the Lee Tunnel consisted of a segmental steel-fibre reinforced primary lining and a cast-in situ secondary lining. Cast using a 360-degree shutter, the concrete was reinforced with Bekart Maccarri’s Dramix 5D fibres, which have been designed for heavy structural applications.

Designer UnPS which is working with the joint venture of BAM Nuttall, Morgan Sindall and Balfour Beatty on Tideway West is looking at radical alternative to the cast-in situ secondary lining: a pre-cast secondary lining.

UnPS senior engineering manager Sotiris Psomas outlines the challenges faced by Tideway’s designers: “The preliminary design is a conventional segmental lining with reinforced concrete secondary lining. The problem with this approach is that very often when the internal pressure is greater than the external pressure, tensile loads develop in the secondary lining.

“If you try to contain the water, you will end up with significant amounts of reinforcement which is counter-productive because of durability issues, but which is needed to be compliant with the structural codes. The other alternative is to add a waterproofing layer between the primary and secondary lining but the installation of a sheet membrane or a sprayable one is labour intense, adding significant cost, time and construction risk.”

UnPS is investigating the precast secondary lining on behalf of the Tideway Alliance, a group set up to encourage collaboration on the programme. The segments would be reinforced with the Dramix 5D fibres which have been designed to exhibit strain-hardening behaviour so that the fibre-reinforced concrete behaves in a similar way to conventionally reinforced concrete.

“We would use the 5D fibres,” says Psomas. “The argument is that the lining has to withstand high surge pressures, it will crack and will be put into tension the same way any secondary lining would be. We would like to
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have controlled cracking to avoid the possibility that, under repetitive transient or impulse forces such as internal surge forces, a crack can develop into a failure mechanism."

Like the Lee Tunnel, the Tideway’s primary rings will be in compression, says Psomas. “The Lee Tunnel and Tideway work if you have pre-compressed rings which is achieved by good tailskin grouting,” he says. "If you cannot achieve tailskin grouting, this is compromised. For pressurised tunnels grouting is a prime implication."

UnPS is working with the Manufacturing Technology Centre in Coventry to develop a non-destructive testing method to check on the annulus grouting. The hope is that it will be ready in time for Tideway. Currently the only method accepted by UK clients to check that the grout has travelled around the whole circumference is to drill through the segments.

Built-in HDPE

In some regions, an HDPE liner is cast into the inside face of the secondary lining to provide additional protection for the concrete against hydrogen sulphide corrosion. DSTT Phase 2 and STEP will both have this arrangement.

On DSTT Phase 1, contractors used a variety of methods for casting the secondary lining. Some cast the arch first, leaving a small section of invert for the second pour; some cast the invert first; two of the Japanese contractors cast the whole lining in one. Whatever casting route is used, the HDPE liners must be welded post-casting at the joints between pours.

An alternative is to attach the HDPE to the segments during the casting process, a process which Herrenknecht Formwork has been developing for a good decade. Though not a solution for deep or large-diameter sewers yet, Herrenknecht’s latest-generation Combisegments are being used on sewer projects in the Middle East, Iran and Canada.

The first version of Combisegments was used on the Yuzhny Sewage Pipeline in Tzarayino, Moscow in 2009. These segments had a cast in GRP liner. In 2013, Herrenknecht Formwork launched a new version which swapped GRP for pDPCD (Polidicyclopentadiene), a polymer which has several benefits over GRP: improved impact and chemical resistance, less rigid and it allowed the EPDM gasket to be incorporated into the mould.

The latest version is different again, described by Herrenknecht in a paper to the WTC 2016. A pDPCD frame, supplied by Telene, holds the EPDM gaskets, supplied by Datwyler, but the liner, from ACRU Kunststofftechnik, is HDPE, also attached to that frame.

Herrenknecht Formwork declined to discuss any of these projects because they are at too early a stage. Feedback from Canada’s Twinning on the West Trunk Sewer Project in Mississauga, a 2.4m-diameter sewer, where Arup is the designer and Technicore is the contractor, should be available towards the end of this year.

**Fibres for durability**

Deep sewer segments must withstand attack from within and without, especially in regions such as the Middle East where the groundwater contains sulphates and chlorides. One example of this is the 9.5km Abu Hamour Surface & Ground Water Drainage Tunnel in Doha, Qatar.

The original specification called for an HDPE liner on the intrados and epoxy coating on the extrados to give a design life of 100 years and a maintenance-free period of 50 years. Design-build contractor Salini-Impregilo proposed an alternative solution, working with the client’s engineer CD Smith, which used a triple-blend concrete and steel fibre reinforcement.

“In the past the key driver for using fibre reinforced concrete was ductility but more and more we see durability as the main criteria, although ductility remains an important factor too,” says Benoit de Rivaz, global business manager for Bekaert Maccaferrì Underground Solutions which supplied fibres to the Abu Hamour project, which was due to complete in the first quarter of this year.

Of the 131 segmental linings for which Bekaert Maccaferrì has supplied fibres, 22 were sewer projects. The first was the Torbay Waste Water Tunnel in the UK in 1999.

Using fibres rather than traditional reinforcing bar limits crack widths; higher numbers of tiny cracks tend to form, which are bridged by the fibres and can self-heal. In an environment where there is chlorine, any ingress of liquid into the cracks in a traditionally reinforced structure causes the rebar to rust and expand, causing further cracking and in some instances spalling. In a steel fibre-reinforced concrete, rusting of the fibres does not have this effect.

Wilhelm Nell, product manager, tunnelling & mining at ArcelorMittal also notes the increased emphasis on durability. “Technical requirements are getting higher and higher, maybe coming first from a durability requirement but then also in relation to performance in general,” he says.

ArcelorMittal has been producing steel fibres for over 30 years, but has recently strengthened its activities in the tunnelling sector enjoying particular success in the rail sector, supplying fibres for most of Crossrail’s tunnel segments in London and for three of the four contracts on the Doha metro. It is also supplying fibres for segments for lot MT501 of the Inner Doha Re-sewage
The use of macro synthetic fibres (MSF) is still in its infancy in segmental linings generally. Elasto Plastic Concrete (EPC) is supplying its BarChip48 fibres to segments for the Santona-Laredo waste water tunnel in Northern Spain. The MSF fibres provide the primary reinforcement with the addition of steel bursting ladders to resist spalling of radial joints.

Two rings for the Euclid Creek Tunnel in Ohio were made using BarChip fibres and the test segments were subjected to handling and jacking trials successfully. A section of BarChip synthetic-fibre-reinforced cast-in-situ lining was also placed as part of the permanent works for the starter and tail tunnels.

Currently, designers have limited knowledge about using MSF for segmental linings, says EPC group chief engineer Dr Ralf Winterberg, who was previously closely involved in the evolution and design of steel fibre-reinforced concrete. “The perception is that the isolated properties of the fibre material will govern the performance of the composite material – the fibre reinforced concrete - but that just isn’t true. ”

“The fact that we generally assess the performance of fibre reinforced concrete for tunnel segments based on beam tests, which favour steel fibre, is flawed”, says Winterberg. “When you look at a typical segmental tunnel, the lining has a high degree of redundancy, allowing stress redistribution, and the rings are under compression so the failure mode just can’t be that of a simply-supported beam with a single crack.”

Unlike rebar or steel fibres, MSF don’t corrode in the presence of chlorine, were fine cracks to form. However engineers must still control crack widths to limit leaks and to allow self-healing of the concrete; a particular problem if surge pressures induce tension in the rings at any time.

As part of its ongoing R&D programme, EPC is developing a new fibre for tunnel segments. “It will have significantly improved performance at fine cracks, further benefitting crack width control,” promises Winterberg.

“The main problem for fibres is that for a long time there was no code or standard for this application,” says Winterberg. Design of fibre reinforced concrete will be included in the revision of EuroCode 2, but it will be largely based on the Model Code MC2010 which is heavily biased towards steel fibres.

Winterberg also cites the ITAtech guidance for some time, ” says Hicks. “They have gone away to think about it.”

VIP polymers is supplying its anchored gasket to the Shieldhall Tunnel in Glasgow, a stormwater storage tunnel for Scottish Water. Trelleborg has also developed an anchored gasket though this has yet to be used on a project. ES Rubber and Italy’s Fama also offer anchored gaskets.

VIP Polymers, ES Rubber and Trelleborg are keen to promote the improved flexibility of their gasket corners. During the installation of some of the early rings on the Lee Tunnel, corners cracked which some attributed to problems with the gaskets.

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With rectangular segments, this could be particularly problematic. “With a corner which is effectively solid rubber, it will only compress so far and then the energy that’s being put into the rubber block to close it down has to go somewhere, so it goes through the concrete and that’s when the concrete can crack,” says Steve Casey, sales and technical director at VIP.

“We haven’t seen glued gaskets in a tender for some time. It’s a major leap forward in my opinion. There are masses of benefits. You don’t have the hazards or mess associated with glue, or problems with gaskets coming adrift. I am determined not to introduce glue into the factory again.”

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SEEDS

Implementation Strategy (IDRIS) in Qatar.

The use of macro synthetic fibres (MSF) is still in its infancy in segmental linings generally. Elasto Plastic Concrete (EPC) is supplying its BarChip48 fibres to segments for the Santona-Laredo waste water tunnel in Northern Spain. The MSF fibres provide the primary reinforcement with the addition of steel bursting ladders to resist spalling of radial joints.

Two rings for the Euclid Creek Tunnel in Ohio were made using BarChip fibres and the test segments were subjected to handling and jacking trials successfully. A section of BarChip synthetic-fibre-reinforced cast-in-situ lining was also placed as part of the permanent works for the starter and tail tunnels.

Currently, designers have limited knowledge about using MSF for segmental linings, says EPC group chief engineer Dr Ralf Winterberg, who was previously closely involved in the evolution and design of steel fibre-reinforced concrete. “The perception is that the isolated properties of the fibre material will govern the performance of the composite material – the fibre reinforced concrete - but that just isn’t true. ”

“The fact that we generally assess the performance of fibre reinforced concrete for tunnel segments based on beam tests, which favour steel fibre, is flawed”, says Winterberg. “When you look at a typical segmental tunnel, the lining has a high degree of redundancy, allowing stress redistribution, and the rings are under compression so the failure mode just can’t be that of a simply-supported beam with a single crack.”

Unlike rebar or steel fibres, MSF don’t corrode in the presence of chlorine, were fine cracks to form. However engineers must still control crack widths to limit leaks and to allow self-healing of the concrete; a particular problem if surge pressures induce tension in the rings at any time.

As part of its ongoing R&D programme, EPC is developing a new fibre for tunnel segments. “It will have significantly improved performance at fine cracks, further benefitting crack width control,” promises Winterberg.

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now, due to the quality of the build and the grouting and the quality of the cast-in gaskets is very good.”

One issue that gasket suppliers can agree on is that many of the gasket specifications they come across are badly written. “In some specification you get elements that have been copied from three or four different projects, putting everything together so that it does not make sense and some of the requirements contradict each other,” says Tiedemann.

Andor Gyurik, sales director for Trelleborg adds: “Gasket specifications aim to capture everything which at times makes them challenging to work with.”

Tiedemann cites specifications for gaskets that can cope with ‘all ground conditions’ or that ask for them to be ‘self-extinguishing’ – an old term that was used for neoprene gaskets. Casey complains about the terminology ‘soft’ corners, saying that ‘compressible’ corners should be used.

“What we would like to see in a specification is the maximum gap and offset condition, the test pressure and the safety margin; it should be clear what is needed,” says Tiedemann.

Casey agrees and adds: “Where a maximum load to closure is specified, it should again be for the whole gasket and not just the straight section.”

Some specifications for sewer segments are starting to call for microbial resistance. “We have been promoting this for many years because microbial attack is detrimental to the performance life of a gasket,” says Casey. “Some suppliers – I’m talking about third-world suppliers – don’t have the knowledge and experience to do that.”

VIP’s tunnel gaskets have always been supplied in materials that have been tested and approved to resist microbial attack, says Casey. Datwyler has recently developed a new anti-microbial compound for sewers.

VIP are supplying a cast-in nitrile rubber (NBR) gaskets to Pre-caster FP McCann for a siphon tunnel at Beckton Sewage Treatment Works in London which is being constructed by Costain, as part of the larger Tideway project. “NBR is often used in ‘brown field’ sites where other rubber compounds such as EPDM may not be suitable,” explains Casey.

“We were one of the few suppliers able to provide NBR gaskets. It requires different tooling, and comes from different sources; we can do it because of our years of experience with our other sealing products.”

Polymer concrete has been used for segmental linings and other structures in sewers. Unlike its cementitious cousin, polymer concrete is not affected by hydrogen sulphide corrosion and therefore does not need additional thin-film sheet plastic linings or coatings to protect it.

The reason why polymer concrete hasn’t been more widely used is that its capital cost is far greater than traditional concrete. Some argue that looking over a 120-year design life, the whole-life cost will be less, but this has not yet been a compelling argument; Kaneshiro cites research that gives certain formulations of polymer concrete a life expectancy of over 300 years.

Kaneshiro notes that recent developments by Solidcast Polymer Technology in the US offer a lower-cost polymer concrete solution: “These technologies incorporate light-weight cores within the precast polymer concrete segment, reducing the overall weight of each component,” he says. “The reduction in polymer concrete weight reduces raw material costs, increases production rates, lowers shipping costs, utilizes lighter-duty equipment and lowers overall installation costs.”

Engineered Cement Composites (ECC) which are reinforced with synthetic PVA fibres are another possibility: “In the past we have trialed ECC in cast-in-situ situations,” says Psomas. “Something similar could be used to create super-efficient segments, to repair segments or even as an annulus grout between the primary and secondary linings.”

In the shorter-term, Psomas sees the need for reduced dosages of fibres as they evolve and the use of GRP cages rather than steel rebar to strategically reinforce certain areas.

“The steel fibre side, there is also a lot of room for improvement,” says Nell. “We are working with our R&D centre on a lot of different things.”

One factor that will drive changes in materials is a reducing supply of PFA (pulverised fuel ash) and GGBS (ground granulated blastfurnace slag) produced by coal-fired power stations and in the production of steel respectively. These materials are used in concrete mixes to improve durability.

“Someone has to come up with an alternative to PFA and GGBS, as these materials are becoming more and more scarce,” says Hicks. “We might see a change in the aggregates we use too; currently recycled aggregates of any form are not allowed in tunnel segments, but that could change.”

The test of any of the newer segmental materials and technologies will be performance over time; the oldest fibre reinforced concrete segments in a sewer are in their infancy in terms of design life at less than two decades old.

We shouldn’t have to wait another 100 years to check on progress, however. Inspections are becoming easier; one of the design requirements for DSTT Phase 2 is that it can accommodate remotely operated vehicles (ROVs) to access the sewer.

“For me, future developments will be driven by long-term experience,” says Nell. “In the future we will be able to check these projects and get information about the long-term behaviour and durability.”

“We know steel fibres give concrete some better properties such as limiting crack widths and better behaviours in terms of impact and abrasion when we test in the laboratory. In 50 years we will be able to see how it behaves in a high-pressure environment, in the real world.”
On November 14, 2016, two Terratec Earth Pressure Balance TBMs (EPBMs) made a historic double breakthrough, marking the end of tunnelling on the Delhi Metro Railway Corporation’s (DMRC) 58.6km Pink Line (Line 7), and heralding the completion of tunnelling for Stage III of India’s most advanced metro project.

With more than double the amount of tunnelling on Phase I and Phase II of Delhi’s metro combined, a total of 36 TBMs were used to bore the 80km of tunnels on Phase III of the system, representing one of the largest urban tunnelling projects ever undertaken.

There have been plenty of challenges for the tunnelling contractors working on the US$5.2bn project. In addition to the usual trials presented by a dense urban capital like Delhi, which is virtually crippled by traffic congestion, difficult mixed ground tunnelling conditions on Phase III have tested the limits of EPB tunnelling, including unexpected full faces of highly abrasive fresh quartzite.

The need to pass beneath operational elevated metro viaducts, heritage monuments of great historic importance, and dense urban areas of dilapidated century-old buildings, also prompted the use of real-time tunnel settlement monitoring for the first time in the city.

The Delhi Metro is India’s first modern metro system and is currently the 12th largest in the world. Devised to be built in sections, construction of Phase I began in 1998 and its first 11km section...
opened in 2002. The full 65km of Phase I was completed in 2006, of which 13km was underground and the remainder elevated. Phase II of the network consisted of 125km of new track, of which 35km was underground, and was fully opened in 2011.

The main components of Phase III are two new metro corridors – The 58.6km Pink Line (Line 7), of which about 19km is underground; and the 35km Magenta Line (Line 8), 23km of which is underground – as well as a 9.4km underground extension of the existing Violet Line (Line 6) to Kashmir Gate.

The overall project is currently gearing up for completion with several sections already in use. When the full Phase III system is fully operational later this year, some 140km of new line will be added to the city’s metro, including 80km of running tunnels and underground connections (the actual twin-tube underground corridor length, including stations, is about 54km). This will expand the metro network to 434km and 308 stations, making it the fourth or fifth largest metro in the world, and daily ridership figures are predicted to rise sharply, from the current 2.8 million to approximately 6.3 million.

The works were divided into 15 main design-build civil contract packages, many of which include elevated metro sections. In order to undertake the tunnelling works, a total of 20 new TBMs were bought by contractors, with the balance of the machines being refurbished from previous projects. Australian-based TBM supplier Terratec proved particularly successful on Phase III, securing orders for eight new EPB machines across four separate contracts on the project.

Perhaps the most challenging of these contracts has been CC-07, on the underground extension of the existing Violet Line (Line 6) to Kashmir Gate (see map), where a team led by main contracting joint venture of Russia’s Metrostroy and local firm ERA Infrastructure encountered a much more varied and difficult set of geological conditions than expected. In addition to highly variable mixed faced conditions with numerous large diameter boulders, the team’s two 6.61m diameter Terratec EPB shields encountered unexpected sections of very hard and highly abrasive full face quartzite.

Located in the heart of Old Delhi, Contract CC-07 involved two sets of twin soft ground tunnel drives: the first running 1.35km southwards from Kashmere Gate – down the western limit of the UNESCO World Heritage Site of the Red Fort – to the Lal Quila Station; and the second set of approximately 620m drives on to the Jama Masjid great mosque.
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Various land acquisition issues caused delays on a number of the Phase III contracts and CC-07 was no exception. Due to an initial lack of site access, shaft excavation at the north end of the alignment was delayed and ultimately the decision was made to reverse the planned tunnelling sequence, instead beginning with the shorter drives from Jama Masjid to Lal Quila. The first TBM to launch was the Terratec S23 machine, in July 2013, on the down-line running tunnel. Its twin, the S24 machine, followed on the up-line tunnel in December 2013.

However, the geology encountered proved quite different to the silt soils and sands that had been expected. “The TBM went through the headwall and started tunnelling in soft ground, as expected,” says Bill Brundan, Terratec’s Site Operations Manager. “Then hard rock started to come in at the bottom of the face and progressed right up to full face.” This rock kept coming and going – ranging from full faces of very hard, fresh or weathered quartzite, to mixed faces with course running sand, and large boulders of up to 4m in diameter.

“We had every possible condition you could imagine,” says Brundan. “Compressive strengths of more than 200MPa in pure quartzite, at the most extreme end of the Cerchar Abrasivity Index, massive fresh blue-coloured quartzite, and large boulders in front of the cutterhead. We even encountered a cavern feature within the rock that was full of sand and water, which required a lot of extra grouting ahead of the cutterhead to stabilize the ground.”

### Table 1: Terratec machine attributes

<table>
<thead>
<tr>
<th>DMRC Contract</th>
<th>CC-07</th>
<th>CC-20</th>
<th>CC-24</th>
<th>CC-34</th>
</tr>
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<tbody>
<tr>
<td>Contractor</td>
<td>METROSTROY-ERA JV</td>
<td>J.KUMAR-CRTG JV</td>
<td>J.KUMAR-CRTG JV</td>
<td>HCC-SAMSUNG JV</td>
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<tr>
<td>TBM Serial Numbers</td>
<td>S23, S24</td>
<td>S26, S27</td>
<td>S25, S28</td>
<td>S36, S37</td>
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<tr>
<td>TBM Type</td>
<td>EPBMs</td>
<td>EPBMs</td>
<td>EPBMs</td>
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<tr>
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<td>6.61m</td>
<td>6.61m</td>
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<td>Dome</td>
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<td>37%</td>
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<td>VFD - Electric Motors</td>
<td>VFD - Electric Motors</td>
<td>VFD - Electric Motors</td>
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<td>960kW</td>
<td>900kW</td>
<td>550kW</td>
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<tr>
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<td>5424kNm</td>
<td>5628kNm</td>
<td>5416kNm</td>
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<tr>
<td>Max. Speed</td>
<td>3rpm</td>
<td>5rpm</td>
<td>3rpm</td>
<td>2rpm</td>
</tr>
<tr>
<td>Max. Advancing Speed</td>
<td>71mm/minute</td>
<td>71mm/minute</td>
<td>71mm/minute</td>
<td>71mm/minute</td>
</tr>
<tr>
<td>Max. Thrust Capacity</td>
<td>40,000kN @ 350bar</td>
<td>40,000kN @ 350bar</td>
<td>40,000kN @ 350bar</td>
<td>40,000kN @ 350bar</td>
</tr>
<tr>
<td>Articulation</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
</tr>
<tr>
<td>Min. Curve Radius</td>
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<td>250m</td>
<td>250m</td>
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</tr>
<tr>
<td>Backfilling System</td>
<td>2-Liquid Type</td>
<td>2-Liquid Type</td>
<td>2-Liquid Type</td>
<td>2-Liquid Type</td>
</tr>
</tbody>
</table>
As well as pushing the limits of EPB tunnelling in very challenging conditions, this ground took a toll on the TBMs, particularly in terms of wear and damage to the machines’ 17” disc cutters. “There was a lot of wear on the cutterheads,” says Brundan. “But that was relatively easy to repair with regular maintenance. The main issue was that we were going through a considerable amount of disc cutters.”

To address this, Terratec – who in addition to supplying the machines and tunnelling equipment on Contract CC-07, also supplied personnel to operate and maintain the TBMs for Metrostroy/ERA – set up a cutter shop on site to refurbish as many discs as possible. “We had planned a cutter shop for Contract CC-24, where we were expecting rock from the start, but we had to bring it in at short notice for CC-07,” Brundan explains.

At its worst, the hard rock seriously hampered progress. However, the 900kW VFD electric driven cutterheads proved themselves more than up to the challenge, maintaining consistent advance rates in the weathered rock of up to 6m per day and up to 20m per day in the soils. Ultimately, the machines each broke through into Lal Quila Station just over a year after their launch, in August 2014 and January 2015, respectively.

The TBMs were then retrieved and set up for their second (1.35km long) drives from Kashmere Gate to Lal Quila, which launched in December 2014 (S23) and April 2015 (S24). Here, the TBMs successfully negotiated the foundations of the existing Kashmere Gate elevated metro station with just 1.2m clearance, an operation that was closely supervised using the extensive settlement monitoring programme put in place by the joint venture.

Fortunately, the ground conditions on these drives were far more in line with the mixed soils originally anticipated across the whole contract, and both TBMs made very good progress. Having excavated a total 3,958m of tunnel, and installed 2,824 traditionally reinforced concrete Universal segment lining rings, the machines made their final breakthroughs in August 2015 and February 2016 respectively.

CC-24 & CC-20

Further south, on the Pink Line (Line 7), four Terratec EPB machines were employed by Indian contractor J. Kumar Infraprojects Ltd. working with China Railway Third Group (CRTG) on two separate contracts, CC-20 and CC-24. Forming a U-shaped loop through the city, the new 59km long Pink Line is set to become the longest metro corridor on the DMRC network. Starting at Majlis Park in the northwest, the line heads south through Delhi Cantt and Mayapuri, before heading east through INA to Lajpat Nagar, where it then heads north again all the way up to Shiv Vihar.

Within this, Contract CC-24 has seen J. Kumar/CRTG JV deliver 6.9km of new metro tunnels running between Lajpat Nagar and Nizamuddin. Completed in three sets of drives – Nizamuddin to Ashram; Vinoba Puri to Ashram; and Lajpat Nagar to Vinoba Puri – the mixed soils encountered were as predicted and the Terratec S25 and S28 TBMs performed extremely well, regularly placing between 15 to 20 rings per day.

However, logistical issues still posed challenges to the progress of the TBMs, including segment deliveries and spoil.
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removal, which were restricted due to night-only truck activity in an already traffic fraught city. “Heavy trucks could only run at night from 10pm to 5am,” says Brundan, who explains that a highly successful day of TBM production could often be followed by the need for slower day, in order to compensate for additional segment deliveries or spoil removal. Land acquisition and station excavation delays also slowed progress, with the TBMs often having to stop and wait at station headwalls for weeks before a breakthrough could take place.

The S25 and S28 Terratec machines ultimately completed their final 970m-long Contract CC-24 tunnel drives between Vinobapuri and Ashram Stations in a double breakthrough on November 14, 2016. They were the last of the eight Terratec machines to complete their journeys, marking the end of tunnelling on the Pink Line and signifying the successful completion of 20 Terratec TBM tunnel drives on the Phase III project.

In practice, two of the Contract CC-24 drives – from Lajpat Nagar to Vinoba Puri – were actually undertaken by J. Kumari/CRTG JV’s other two Terratec TBMs, which were purchased for its Contract CC-20 drives. This was due to work on CC-20 also being delayed by a land acquisition issue.

To the west of Lajpat Nagar, Contract CC-20 includes 2.2km of new line between Mayapuri and Delhi Cantt, with an intermediate station at Naraina. Despite preparation works at the Naraina work site being fairly advanced, a small parcel of land in the middle of the site that included several shops and residences remained in dispute, and this was blocking the excavation. In order to offset the impact of this delay, the CC-20 TBMs (S26 and S27) were relocated to Contract CC-24 in the summer of 2014 to complete the twin 800m-long drives between Lajpat Nagar and Vinoba Puri. The drives were completed in October and December of 2014, and by early 2015 the machines had returned to CC-20 to start their original drives from Delhi Cant to Naraina.

Unlike Contract CC-07, full faces of hard rock had been anticipated along the length of the Contract CC-20 alignment and steady advance rates of about 12m per day were consistently achieved on this contract. “The S26 and S27 machines were designed to perform more as rock EBMs,” explains Brundan. “They had more powerful screws, which were located further forward on the machines so the rock could be taken out of the cutterhead. With a 960kW drive, they also had a bit more power, so they were set up to manage the conditions.”

CC-20’s first set of 820m long drives were both completed in late 2015 and, following a short stop at Naraina, the second set of 310m drives got underway and broke through at Mayapuri in February and March, 2016, respectively.

Contract CC-34

On the Magenta Line corridor (Line 8), Contract CC-34 was actually the first of the contracts using Terratec TBMs to be completed in full. Delivered by a joint venture of Hindustan Construction Company (HCC) and South Korea’s Samsung Engineering and Construction Group, Contract CC-34 forms the most westerly section of the new 38km-long line between Janakpuri West and Botanical Garden. Running 3.6km from Janakpuri West to Palam Station, Contract-34 involved three sets of drives. The first of these started in July and August 2014, at Vikaspuri Station, and broke through 215m later at Kerala. From there both Terratec TBMs (S36 and S37) were moved through the station to begin their second 250m-long drives to Janakpuri West. As these drives came to an end, the TBMs successfully negotiated the foundations of the existing Janakpuri elevated metro station with just 3m clearance.

The geology throughout the alignment was composed of very wet silty clay and dry sandy soil. Therefore, in contrast to the other Terratec EPBMs on the project, these TBMs were designed with a spoke-type cutterhead with a 57% opening ratio.

Both TBMs passed underneath residential areas and came in close proximity to a number of sensitive structures, including a major highway flyover, requiring very accurate settlement control in critical zones.

The CC-34 contract drives were completed in August 2015, with the second TBM (S36) breaking through at Palam Station a month after its twin (S37). The performance of the machines was recognised at the breakthrough ceremony by Mr. Raman Kapil, Project Director of the joint venture. “We are thankful to all of our sub-contractors and equipment suppliers, especially Terratec, as these TBMs have excavated very smoothly and this has helped us to complete the works ahead of the planned schedule.”

Looking ahead

All tunnelling works on Phase III of the Delhi Metro were completed by the end of November last year. The Violet Line extension – now also known as the Heritage Corridor – is expected go into service within the next few weeks, while the other lines will go into operation in stages with the full system due to be up and running by the end of September.

However, with the government having given the green light to the much awaited Phase IV of the metro this January, DMRC is very much looking to the future. Phase IV will include six new lines, adding a further 104km to the network and boosting connectivity to the capital’s outskirts, the airport and south Delhi. These lines, which include 36km of tunnelling and 28 underground stations, are expected to go out for tender within the next couple of months.

They include: a new 20.2km line between Tughlakabad and Aero City, which will include 14km of tunnels and 10 underground stations; a new 7.96km line between Lajpat Nagar and Saket G Block, which includes 2km of tunnels and one underground station; a 21.7km elevated extension of the existing Red Line from Rithala to Narela; a 28.92km extension of the Magenta Line from Janakpuri West to RK Ashram (via Majlis Park), which includes 7.2km of tunnels and 7 underground stations; a 12.54km elevated extension of the Pink Line from Mukundpur to Maujpur; and a new 12.58km long underground line between Inderlok and Indraprastha, which includes 10 underground stations.

Following the completion of Phase 4, which is slated for 2021, the Delhi Metro is projected to become one of the largest metro systems in the world, carrying about seven million passengers every day.
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Blow-out failures part 2: purely cohesive soils

Introduction
As mentioned in the previous issue, a blow-out is a general term, which refers to any sudden release of face pressure. There are several ways in which a blow-out can occur in a purely cohesive soil:

1. Passive failure
2. Softening and erosion
3. Hydraulic fracturing

Passive failure is like a stability failure in reverse: a large cone of soil is forced upwards or outwards, failing along large shear surfaces. The main difference to stability failure is that the weight of the soil is a favourable rather than an unfavourable load, and the volume of soil involved is usually larger. Therefore, passive failure requires high face pressures.

Blow-outs can also be caused by support fluid finding a path to the surface, for example up a poorly-backfilled borehole, or by creating a path through erosion or hydraulic fracturing. Blow-outs can also occur away from the face – anywhere that an excessive pressure is applied. For instance, due to excessive grouting pressures, or excessive internal tunnel pressures finding a way through the lining.

Looking back at the Docklands Light Railway tunnel blow-out described in the previous issue, compressed air was needed for construction of a crosspassage between the two running tunnels near the deepest point under the River Thames, where the water pressure was about 2.7 bar at axis level (270 kPa). One bulkhead was 60m beyond the crosspassage and the other one was much further inbye towards the portal, where the cover was only 8m, as shown in Figure 1. The blow-out occurred near the inbye bulkhead through the tunnel lining as the bulkheads were being tested up to 3 bar and pressure had reached only 2.1 bar (210 kPa). Eight of the tunnel's 1.2m long precast concrete rings were blown apart by the blast (Jones, 1998), and a crater 22m wide and 7m deep was created by the blast. The full overburden pressure at the crown at this location was less than 160 kPa. It is not known whether this blow-out began as a hydraulic fracture and the large crater was due to the huge volume of air that was released, or whether it was a passive failure.

Softening and erosion
Softening and erosion appears to be most common for pressurised water conveyance tunnels during operation where the head of water is greater than the distance to the top of the clay or the surface. A leak out of the lining can, over time, gradually soften and erode the clay, eventually creating a path out of the clay to the surface or into a more permeable soil, resulting in flooding and/or excessive loss of water from the tunnel. This happened to a raw water tunnel near the village of Datchet, near London Heathrow Airport, in 2006, where over 30 years of water eroded a path through the London Clay and then suddenly burst out, spouting 5m into the air and producing flood waters 1m deep (BBC, 2006). Fourteen properties were flooded, most only in their gardens, before the tunnel could be isolated. This was an unbolted concrete wedgeblock tunnel that softened and erosion will take to compromise a tunnel is difficult. However, it is considered good practice nowadays to design a tunnel lining to be watertight for water conveyance in soft ground, and so this risk hopefully only applies to older tunnels.

Hydraulic fracturing
Hydraulic fracturing is a localised effect that can happen in the short term, or may occur after some softening and erosion has reduced the effective cover. This is where the clay is fractured by a high localised fluid pressure that exceeds the tensile or shear strength of the clay (Marchi et al., 2014), creating a path for the escape of support fluid. This will
usually occur at the crown of the tunnel. In a tunnel with compressed air, the loss of air pressure could be followed by flooding of the tunnel and/or collapse of the face. In a slurry TBM, a sudden loss of slurry can be followed by over-excavation due to failure of the face caused by loss of support pressure. Also, release of the slurry at the surface or into an overlying lake or river could have environmental consequences.

For hydraulic fracturing to occur, a rule of thumb is to assume the fluid pressure has to exceed the full overburden pressure of soil and water (Holzhäuser, 2003), and generally accepted practice is to limit support fluid pressures to this value (e.g. Guglielmetti et al., 2008). This is usually significantly lower than the pressure needed for passive failure to occur.

Bezuijen & Brassinga (2006) show from field data and centrifuge tests that bentonite slurry blow-outs caused by hydraulic fracturing can occur at much lower face pressures than those needed for passive failure predicted by finite element or kinematic analysis methods. This is because these methods do not take account of the fact that slurry is a fluid. Bezuijen & Brassinga found this limit to be approximately the pore pressure plus 2 to 3 times the effective stress for their case.

Marchi et al. (2014) show from a large number of experimental tests and case histories of fracture grouting that fracture initiation in clay may be caused by either tension or shear. The most important factor is the confining pressure, otherwise known as the minor principal stress. As fluid pressure increases, the radial stress in the surrounding clay increases but the circumferential stress decreases. Failure occurs either when the circumferential stress reaches the tensile strength or when the difference between the radial and circumferential stresses causes shear failure. Other factors, such as the water content of the clay, the liquidity index, the stiffness, rate of pressure or injection contribute, but the lower bound to all the measured fracture pressures was the initial confining pressure, so it seems the fracture pressure cannot be lower than the minor principal total stress.

The pressure at tensile fracture is given by (Mitchell & Soga, 2005):

\[ P_f = 2\sigma_0 - u_0 + \sigma'_t \]

where \( P_f \) is the fracture pressure, \( \sigma_0 \) is the initial confining pressure (the minor principal total stress), \( u_0 \) is the initial pore pressure and \( \sigma'_t \) is the tensile strength.

The pressure at shear fracture is given by (Soga et al., 2005):

\[ P_f = \sigma_0 + n\sigma_u \]

where \( n \) is a constant and \( \sigma_u \) is the undrained shear strength. For a clay with a positive liquidity index, \( n = 1 \), but for a clay with a negative liquidity index (i.e. the water content is below the plastic limit) \( n = 1.5 \) to 2.

Therefore, either the minor principal total stress or the lower of the tensile or shear fracture pressures should be set as the maximum face pressure when compressed air or slurry is used.

**Passive failure**

Since hydraulic fracturing is the critical mechanism when support fluid is used, passive failure in clay is only likely to be the limiting case for earth pressure balance TBMs. Most studies of passive failure in clay, involving numerical models or kinematic limit state analysis, have assumed a uniform face pressure (Mollon et al., 2013), whereas in an EPB machine we would expect a face pressure that increases with depth. Despite this shortcoming, a design chart by Mollon et al. (2013) based on their asymmetric ‘M2’ velocity field method is shown in Figure 2, with values given in Table 1 to aid interpolation for design purposes. The values of \( N_f \) and \( N_c \) from the design chart should be used in the following equation:

\[ \sigma_b = \gamma DN_f - cuN_c + \sigma_s \]

where \( \sigma_b \) is the critical face pressure for a passive failure blow-out, \( N_f \) is a stability number taking account of soil weight and \( N_c \) is a stability number taking account of soil cohesion. This equation is derived from the more general stability equation, which is:

\[ \sigma_c = \gamma DN_f - cN_c + \sigma_s \]

where \( N_f \), \( N_c \) and \( N_s \) are stability numbers for the effect of soil weight, cohesion and other effects, respectively. For undrained constant volume behaviour, \( N_f = 1 \) and \( c = c_u \). In order to make the equation equal to the undrained stability equation traditionally used for clays, all that is needed is to substitute \( N_f = C/D + 0.5 \) and \( N_c = N_c \). But in Mollon et al.‘s ‘M2’ velocity field method, \( N_f \neq C/D + 0.5 \), because the velocity field is asymmetric (the maximum velocity is set 0.4D above the centre of the face), so the more general form must be used.

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**Figure 2: Design chart for critical passive failure blow-out (from Mollon et al., 2013).**

**Table 1: Values used to produce Figure 2 for critical passive failure blow-out (from Mollon et al., 2013).**

<table>
<thead>
<tr>
<th>C/D</th>
<th>( N_f ) (passive failure blow-out)</th>
<th>( N_c ) (passive failure blow-out)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.98</td>
<td>-7.02</td>
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</tr>
<tr>
<td>3.0</td>
<td>3.39</td>
<td>-14.80</td>
</tr>
</tbody>
</table>
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Unfortunately, no centrifuge modelling of passive failure in clay has been published, but it is corroborated to some degree by Mollon et al.’s (2013) numerical modelling of a heading using FLAC3D, for which a comparison is shown in Figure 3 for $D = 10$ m, $\gamma = 18$ kN/m$^3$ and $c_u = 20$ kPa.

centrifuge testing produced by Kimura & Mair (1981), for the same geometry $D = 10$ m and $P = 0$ m, soil bulk unit weight $\gamma = 18$ kN/m$^3$ and undrained shear strength $c_u = 20$ kPa. The aim of design would be to find a safe zone of face pressures between collapse and blow-out, allowing for factors of safety and for variability of blow-out scenarios.

Numerical and physical modelling appear to be fairly reliable methods of analysing collapse or passive failure of a heading. However, there has been much more focus to date on collapse and more research is needed to improve our knowledge of passive failure and blow-outs in general. Although relatively rare, the effects can be just as catastrophic as a collapse.

Figure 3: Comparison of critical passive failure pressures using the design chart based on ‘M2’ velocity field kinematic analysis by Mollon et al. (2013) and a 3D finite difference model in FLAC3D, also by Mollon et al. (2013), for $D = 10$ m, $\gamma = 18$ kN/m$^3$ and $c_u = 20$ kPa.

Figure 3 shows that the kinematic analysis overestimates the critical passive failure pressures compared to the numerical modelling results. This is unsurprising because it is an upper bound and defines when the ground must fail, and therefore will always be on the unsafe side. However, it must be close to the true collapse geometry and conditions, as it is not too far above the FLAC3D results.

Figure 3 also gives us a feel for the magnitude of face pressure required to cause passive failure. Even for this low value of undrained shear strength (20 kPa), the critical face pressure is about 1.5 times the full overburden pressure at axis level. At an undrained shear strength of 30 kPa the critical face pressure is double the full overburden pressure (Mollon et al., 2013). Therefore, when support fluid is used, hydraulic fracturing will almost always be more critical.

Also shown on Figure 3 is the minimum face pressure required to avoid collapse, from the design charts based on the applied pressure. In very weak soils at low cover, a safe zone may be impossible to achieve.

In summary, to estimate the critical face pressure that would cause a passive failure blow-out, the design chart in Figure 2 could be used to provide an initial estimate, and if accuracy is of critical importance, or if soil layers or geometry are complex, a 3D numerical model could be used. Where a fluid such as slurry or compressed air is used for face support, a hydraulic fracturing blow-out is more likely, and face pressures should be limited to below the hydraulic fracturing pressure calculated at the crown of the tunnel.

Conclusions

There are many types of blow-outs, of which passive failure is just one. For all types of blow-outs, increasing cover will generally reduce the risk, but an understanding of the ground and the groundwater, and how they interact with the support method, will help predict

REFERENCES


THERE CAN BE NO DOUBT that subsurface construction projects require specialist contractual frameworks. Within these contractual frameworks, it is of paramount importance to manage the risks specific to underground projects such as uncertainties regarding the geological, geotechnical and structural performance of the subsurface space. Thus far, no internationally recognised standard forms for underground tunnelling contracts exist. The International Federation of Consulting Engineers (FIDIC), in cooperation with the International Tunnelling and Underground Space Association (ITA), is about to close that gap. The two organisations are jointly developing specific Conditions of Contract for Tunnelling and Underground Works under the working title ‘Emerald Book’.

Cooperation between ITA and FIDIC
The ITA has long since recognised the key role of contractual provisions. In 1974, the ITA established a Working Group on Contractual Sharing of Risks (today ITA Working Group 3). The Working Group has since published recommendations on a large variety of contractual topics. One key concern has been to find ways to equitably distribute underground risk between owner, contractor and consultant. The recommendations further dealt with, inter alia; changed conditions clauses; full disclosure of available subsurface information; and the pre-qualification of contractors.

Additionally, since the 1970’s, ITA officials began discussions with representatives of FIDIC to include the ITA recommendations into FIDIC Conditions of Contract. These Conditions of Contract published by FIDIC are probably the most frequently used contract forms for international infrastructure projects.

A contractual standard specifically for the tunnelling industry is fast emerging on the horizon – the New FIDIC ‘Emerald’ Book.
Ulrich Helm, Partner, and Fabian Bonke, an Associate, of the international law firm Hogan Lovells International LLP explain
FIDIC has published a variety of different Conditions of Contract, which are now (unofficially) referred to according to the colour of their bindings: most renowned being the Red Book (building and engineering works designed by the employer) and the Yellow Book (building and engineering works designed by the contractor). In recent years FIDIC has published many new Conditions of Contract and the new – possibly Emerald coloured – book on Tunneling and Underground Works will soon complement the FIDIC suite.

To this end, ITA and FIDIC in 2014 set up the shared Task Group 10 “Contract Form for Tunneling and Underground Works” which consists of 3 members from FIDIC (Jim Maclure (United Kingdom), Gösta Ericson (Sweden), Hannes Erdl (Austria)) and 4 members from ITA (Andres Marulanda (Colombia), Charles Nairac (France), Martin Smith (United Kingdom/Korea) and the Chairman Matthias Neuenschwander (Switzerland)). In close cooperation with ITA Working Group 3, the shared Task Group 10 have met more than ten times so far taking its decisions unanimously.

**What stage is the project at now?**

In 2014, FIDIC and the ITA, upon proposal of Task Group 10, decided initially to develop a self-standing FIDIC book instead of solely providing a set of Particular Conditions to adapt an existing FIDIC book to the peculiarities of underground works. So far, the Task Group 10 has created a first draft of the General Conditions, which passed the Limited Internal Review by FIDIC, and the ITA. Other ITA Working Groups, the ITA Executive Council and stakeholders such as the European International Contractors, promoting the interests of the European construction industry, have been informed about the state of works. The next steps are for a Draft of Guidance for Conditions and for Tender Documents, and a Draft Foreword to be presented most likely during 2017. It is currently under discussion whether or not to provide users with a first test edition available for a two-year period, possibly in 2019/2020 and then afterwards with the final edition.

**The need for new FIDIC conditions of contract?**

The fact that contracting practices for tunnels must be dealt with in a different manner than other types of construction is already well recognised in the underground construction industry. The contractual approach has, however, been variable. Frequently contractual frameworks are uniquely drafted for one project. Occasionally, standard form contracts are used taking other FIDIC books or the New Engineering Contracts (NEC) as a point of departure. For the risk allocation, parties sometimes rely on national standards such as Swiss Code 118-198 (2004), General Conditions for Underground Construction Works. Valuable guidance for contracting risk allocation (but also with regard to other key contractual practice areas relevant for subsurface construction projects) is also provided by ITA in Recommendations, Guidelines and Checklists.

The new FIDIC Conditions of Contract for Tunneling and Underground Works could now close the gap and establish a contractual industry standard. It would recognise the uniqueness and complexity that has to be dealt with in underground construction projects. Underground works are special in terms of risk management and allocation because of unforeseeable risks caused by unpredictable ground behaviour. And underground construction projects are particularly complex and the complexity in project delivery models is ever increasing. The availability of a contractual standard could improve legal predictability for the industry and thereby contribute to the growth in the market.

**Structure of new FIDIC Conditions of Contract**

The new FIDIC Conditions of Contract will come as a self-standing new FIDIC Book, including General Conditions of Contract and Guidance Notes to Particular Conditions and to the Preparation of Tender Documents. The FIDIC Yellow Book will serve as a model document with adjustments based on careful reading of the FIDIC Pink Book (which is a variation of the Red Book used by Multilateral Development Banks) and to the FIDIC Form of Contract for Dredging and Reclamation Works. Most of the provisions of the FIDIC Yellow Book will thus be inserted unchanged into the new FIDIC Book. In the current draft version, approximately 10% of the Yellow Book sub-clauses have been amended to accommodate the contractual challenges typical to underground construction.

**Allocation of risk**

One of the key elements of the new FIDIC Book is the standard contractual risk allocation which has been developed in accordance with basic risk management principles. Hereafter, the risks of unexpected subsurface and groundwater conditions lie with the employer as the party who can best control these risks. This seems justified since the employer benefits most from a completed project, the employer should, on the one hand, pay if the subsurface conditions are worse than anticipated and, on the other hand, benefit if the ground is better than anticipated. The performance risk, on the contrary, lies with the contractor as the party who can best handle expected ground conditions.

**Key Role: Geotechnical Baseline Report and Baseline Schedule**

A key role for the allocation of risks in the new FIDIC Book will be assigned to the so-called Geotechnical Baseline Report (“GBR”). The “GBR” sets out the sub-surface conditions anticipated under the contractually agreed underground excavation and lining design and construction methodology, and states the allocation of the risks for sub-surface conditions between the parties. The GBR shall be incorporated within
the contract documents taking priority over General Conditions.

Based on and consistent with the Geotechnical Baseline Report, another key document is developed: the “Baseline Schedule”. It contains the anticipated work items and activities related to the underground excavation and lining, such as ground treatment, excavation or ground support measures, with the respective production rates.

Adjustments to time and price

As subsurface construction projects must deal with the scrutiny of scheduling on the one hand, while on the other hand the specific geological circumstances require for a flexible accommodation of unforeseen events, the new FIDIC book on Tunnelling and Underground Works will provide for predicted.

Furthermore, the contractor shall benefit from a bonus payment if the construction is successfully completed by the contractor prior to the date fixed for completion in the contract.

Key Role: Engineer

The new FIDIC book assigns a strong role to the engineer. He is acting, on the one hand, as the employer’s agent and, on the other hand, with a strong independent judgment. This double role is a common feature in the different FIDIC books but requires a high degree of impartiality and fairness from the side of the engineer. The engineer undertakes a broad range of measures associated with the correct day-to-day administration of the contract and plays a central role in resolving disputes. The new FIDIC book will assign, inter alia, the following tasks to the engineer:

- Determination of necessity of safety, stability, timely progress and completion measures;
- Overview of measurement of underground excavation;
- Adjustment of contract price

Dispute resolution process

In line with the other FIDIC books, the new FIDIC book provides for a three-step procedure for the purposes of dispute settlement. First, any dispute has to be referred to the Dispute Adjudication Board (DAB) which consists of one expert or a group of experts. As is the case with all future FIDIC projects, the DAB is appointed permanently for the term of the project and not ad hoc for one single dispute. The DAB renders a temporally binding decision. Second, the party dissatisfied with the DAB decision might seek a last attempt at dispute avoidance and amicable settlement may be reached. Third, the dispute may be referred to arbitration governed by the rules of arbitration of the International Chamber of Commerce (ICC) where the dispute will be finally settled.

The provided dispute resolution mechanism has already proven to be successful in the other FIDIC books. The availability of a standing DAB assists in avoiding disputes and provides for quick decision-making which is essential in large construction projects. This FIDIC approach is in line with the dispute resolution mechanisms suggested by ITA for tunnelling projects. In fact, ITA recommends DAB and arbitration as the best fora to resolve these complex disputes.

Conclusion

The new FIDIC book has the potential to develop a contractual standard for the tunnelling industry. It adapts worldwide established FIDIC rules to the particular needs of the underground construction industry, in particular with regards to the risk allocation and the complexity of the projects. The development of such a contractual standard could enhance legal predictability in tunnelling projects and thus contribute to economic growth in the business sector as a whole.

It is, however, clear that in view of the variety of contract situations the FIDIC book cannot be a “one size fits all” solution. The parties’ different contractual needs and interests impact the suitability of contractual provisions. For example, will the employer’s and contractor’s experience and know-how determine the choice of design-bid-build contract, design-build contract or a combination thereof. Also, the parties’ interests with regard to the allocation of risks for pricing and timing might differ from project to project. In order to facilitate an adaptation to project specific issues, the new FIDIC book will provide valuable guidance in its FIDIC Particular Conditions, which can be used to modify the General Conditions. It is, however, of paramount importance that no ambiguity is created, either with the General Conditions or between the clauses in the Particular Conditions.

Tailor-made advice may be required to conduct a risk assessment of the FIDIC book with regard to the applicable contract law. Since the FIDIC book is a contract agreed on by the parties, issues such as the interpretation and validity of its provisions are to be determined according to the applicable contract law. Therefore, it is not uncommon that the contractual provisions are interpreted differently under national laws. It is also possible that the governing law might, in exceptional cases, actually override provisions of FIDIC. This concerns, in particular, provisions on damages or limitation of liability which are often critically viewed under national contract laws and therefore require careful consideration.

The new FIDIC book will provide valuable guidance in its FIDIC Particular Conditions, which can be used to modify the General Conditions.

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Automated design in practice

Ian Turner, Atkins tunnel engineer and software developer here describes a new framework for automated tunnel design

AUTOMATED DESIGN IN TUNNELLING has a long history. Spreadsheets such as Lotus 1-2-3 have been used to automate tasks such as the production of Moment capacity curves since the mid 1980’s. There are some clear efficiencies from this automated approach but tunnel design can still be a highly iterative process and a process that can be highly repetitive. Bespoke designs are needed for some structures but shafts, pipe jacks, and other standardised elements are often unnecessarily designed inefficiently. Modern engineering is so much about speed. Design iteration and modifications matter. Clients and builders want to understand the implications of options, and yet for designers this can be a major challenge. The nature of tunnelling is that space is critical. A change to one component can knock onto many others in trying to optimise both the spatial geometry as well as addressing structural changes as elements get bigger. The space required to build a structure is also critical to the design and optioneering process with shafts often designed around the space required for construction rather than operation.

Before looking into a framework for how tunnel designs could be automated we need to consider how this differs from some other design automation. It is not to be considered a tool for the generation of highly optimised designs intended to achieve maximum structural efficiency for a given problem. There are structures and construction methods within tunnel engineering that may benefit from this approach but efficiency is often best achieved simply through considering aspects such as constructability, efficient use of space and avoiding errors and rework.

Also, automation should not be considered as the generation of parametric 3D models using tools like Dynamo\(^\text{\textregistered}\). In this approach the geometry of a 3D model is defined by a set of variables and the relationships between structures rather than by fixed numbers. 3D models can then be automatically regenerated in response to a change in the input values, such as a change in alignment or construction tolerances. This approach has some value in major projects but in typical smaller projects we need something that is well documented, repeatable and easily expandable. Dynamo is an exceptional tool for geometric modelling but this is only one aspect of creating a tunnel design with issues like documentation and structural design that also need to be taken into account.

As an example
By way of an example of the application of this framework, consider a specific case of the base of a shaft with a pipe jack breaking out. This is a relatively simple problem but is a useful example of how the different parts of the framework will work. The first aspect to consider is the design methods to be used. One of the aims of this framework is to produce a fully code compliant design together with the associated documentation to a detailed design standard. For most structures a single calculation approach will not therefore suffice and a number of different calculations, possibly with different approaches and different analyses will have to be undertaken. The calculation method and approach should also be both human readable and fully human checkable. This is a critical part of the proposed framework because it limits the pressure on getting the code perfect and emphasises the production of correct human checkable calculations. This means that the development of detailed protocols for design is an essential early activity in developing the framework. These protocols should be a step-by-step process to undertake the design of any element of the tunnel. It should be precise and procedural as well as being comprehensive and as adaptable as necessary to cover all the reasonably foreseeable design cases. As the aim...
throughout is to ensure that the design methods adopted are fully human checkable, complex analyses such as Finite Element is to be generally avoided.

It is worth noting that these design protocols, if well written by engineers with sufficient design experience are useful design documents in themselves. In the author’s experience the more specific these documents are the more effective they are as design documents. It is also important to bare in mind that the design protocols will never be sufficient to cover every case that we have to design, but it should be sufficient to cover a significant majority of the cases that we consider and it is these cases where the most efficiency and speed can be gained from design automation.

The relationship of the design protocols to the rest of the framework are shown in Figure 1.

Next up
The next stage in developing the design is to map out the spatial requirements of the structure. This is all of the expected uses of space within the tunnel. The aim is to let the computer determine a layout that works based on the requirements of the structure. There are two aspects to define for each structure, its shape and size and any constraints or aspirations that link it to other structures or components in the tunnel. The shape definition can be as complex as necessary with each component either represented by a simple rectangle or circle or they could be defined by detailed definitions of the exact shape.

When mapping out the requirements of the structure it is important to understand the difference between a constraint and an aspiration. A constraint is considered to be a binary requirement - does a structure satisfy it or not? Typically constraints have to be satisfied for an adequate design of a structure, although in some cases constraints could be optional in a satisfactory design. A typical example might be the level of a base slab where a structure is intended to follow a specific hydraulic gradient. Code compliance issues are often also binary constraints. Aspirations are similar to constraints but are more like variables, typically either maximised or minimised. Minimum overall cost and construction programme are the simplest aspirations but others such as minimising the settlement impact on a specific structure could be considered.

At the lowest level most of the constraints and aspirations will be low-level relationships between one structural element and another. For the most part there will be a simple relationship that says that no structure should clash with another, however the relationships can be more complex. A simple case might be a ladder, which is intended to be fixed to a shaft wall. The constraint in that case might then be the ladder is to be inside the shaft with a 100mm offset, a tolerance of 20mm and positioned radially to the shaft centre. Other geometric constrains might include a requirement for two elements to be adjacent to each other, or a simple constraint on the global position of an object where it has to exactly meet an existing structure or another part of the new works.

A way to visualise all of these constraints and aspirations is as a matrix with the rows and columns each formed from one structure. Each cell in the matrix then defines the relationship between one structure and the next. This matrix will be known as the Constraints and Aspirations Matrix (CAM). A simple example of a CAM is shown in Figure 2.

From this model a structural layout needs to be generated. In some cases it may be possible to directly calculate an optimum solution where the relationships between structures are simple and optimisation is only taking place on one axis, however in most cases defining a solution is far more complicated than this. The human approach to solving this sort of problem is often a combination of designer’s intuition and design iteration. Designers intuition is however difficult to replicate within a computer whilst design iteration can be undertaken rapidly, accurately and efficiently by a computer. The challenge then is to identify optimum solutions using a purely iterative approach.

A new approach
The approach proposed within this framework is to use a simple evolutionary algorithm to solve the problem. The position of all the structures within the tunnel are defined using a series of simple codes such as (Vertical Ladder, 900, 2500, 10000, 270) defining a vertical ladder 900mm in diameter, with an xx coordinate of 2500mm and a yy coordinate of 10000mm and rotated 270° to the global axes. All elements are initially defined a randomised location and a Goodness of Fit Test (GoFT) is run against the matrix of constraints and aspirations. The GoFT defines how well the structure matches the constraints in the matrix and if the GoFT gives a sufficiently high score then that layout is adopted. If it is not considered good enough then the layout is slightly randomly adjusted and the GoFT is rerun. There are a number of improvements that can be made to this simple algorithm to do things like hunt for widely varying results or to speed up iteration towards a good solution, however the basic approach remains the same.

The aim of this model is to generate something close to an optimum layout given all of the constraints, however we have to expect that there may be issues with the final layout generated after many iterations.

Typical issues might be:

• Whilst the tool will be designed to optimise the problem so far as possible, it is entirely possible that either it does not find a solution that satisfies all constraints or that all of the constraints defined form a problem that is impossible to solve.

• It is intended that this framework produces a tool that is flexible and easily updatable as designers encounter problems and structural forms that they have not previously worked with. This necessarily means that the code for generating the layout needs to be modular and extensible but in order to gain the benefits of speed it must be relatively lightweight. It might therefore be expected that the code will not perfectly address issues like edge cases that more comprehensive code might cover.

• It will not be uncommon for the generation of a correct list of constraints to be an interactive process as some constraints are initially forgotten and only identified by reviewing generated designs. These issues mean that producing a quality report on the outcomes of the optimisation process is essential. The tool needs to generate warnings where issues have been identified. It should also generate a report on each structural component identifying the specific layout and giving a dimensioned sketch of the components position and relationship to all other critical components. This report is intended to be reviewed by the engineer generating the design and enable the engineer to rapidly assess whether the generated design is adequate or not. The quality of this report is therefore an essential component of this framework for automated design. An example of a typical report considering the space-proofing of the problem considered previously is shown in figure 3. It is worth noting at this stage that the report on the space proofing will not be reviewed prior to undertaking structural or other similar designs. To consider the reason why, consider a break out at the base of a shaft supported by a steel picture frame type arrangement. The space taken by this picture frame is directly related to the structural design of the frame. A situation can be envisaged where the frame is initially assumed to be a certain size. Based on the proposed layout and the structural design of the frame it is determined that the frame size must increase. This increase in the frame size then means there is insufficient space in the base of the shaft to include the larger frame and so a larger shaft must be adopted. The large shaft then imposes a higher hoop force on the steel frame requiring an even larger frame. These structural design iterations will have to be included in the optimisation algorithm so the GoFT will typically be undertaken only after structural calculations have been undertaken by the tool so that the individual member sizes can be confirmed.

Integrated structural calculations are therefore also included in the additional component to any tool that is intended to undertake a complete and code compliant detailed design of any structure as part of the design process. By doing this, design failures - where estimates of structural component sizes are incorrect early in the design process - can be avoided. In common with the space-proofing component the structural design tool should:

• Undertake structural design in a manner that is human checkable rather than using complicated analysis approaches.

• It should be comprehensive so all necessary checks are undertaken.

The aim of this framework is not to produce highly efficient structural designs, but to practically achieve a completely automated structural design. As such the design approaches whilst efficient should prioritise simplicity and comprehensiveness over achieving structural efficiency.

In common with the space-proofing tool, the quality of documentation of the structural design of the tunnel is essential. The design calculations should be fully automated including all necessary checks for a particular structure and following the design protocol previously defined. This will enable the designer to review the design in entirety and sign off the design undertaken with no further calculations necessary.

**Other automations?**

It can easily be envisaged that other design components could also be considered for automation. Settlement and damage calculations is an obvious area for automation with individual building assessments rapidly undertaken for each design iteration. Constraints and aspirations could then be included by treating them as a structure with a fixed location. All constraints such as damage categories can then be defined in the CAM for this structure and the GoFT would then include checks against these constraints. The same approach could be applied to other designs that can be readily automated such as drainage.

With this framework it is clear that there are a number of higher-level areas that are not addressed by the framework. Elements such as concept design, selection of construction methodology and risk management are deliberately not considered. The aim is to automate those tasks that can be relatively easily automated in a procedural manner minimising the design effort needed to undertake these activities. The framework will not work for a certain proportion of cases or for some parts of some structures or for highly complex structures in their entirety. However it will automate day-to-day design activities that are prone to be time consuming and which can be iterative. It also allows design changes to be considered in great detail with both speed and within the context of a well-defined set of constraints of the structure. All of these areas will dramatically reduce the design cost or improve the efficiency of undertaking design changes whilst ultimately improving design consistency and design documentation.

In considering this framework it is clear that automation is not without challenges. The key challenge is clearly in developing
We have to expect then that whilst design automation could ultimately result in fewer design engineers, the knowledge and skill of those remaining engineers has to increase, rather than decrease.

engineers for a new approach to the design of tunnelled structures. The design process is no longer adaptable to the tools and technologies known by the designer. The design tool fixes the design approach. It is also comprehensive, requiring designers to have a similarly comprehensive understanding of the design approaches used. And yet, in many ways the design framework is stupid, it will not understand all of the limitations of the design approaches it uses, only those limitations it has been explicitly taught within the code. Not only does the designer have to comprehensively understand the design methods used by the design tool but they have to understand the limits and be able to recognise them without the time and space usually given when undertaking a structural design in the standard manner.

We have to expect then that whilst design automation could ultimately result in fewer design engineers, the knowledge and skill of those remaining engineers has to increase, rather than decrease. This is analogous to a pilot moving up from a single engine plane to flying a passenger jet. The fundamental flying skill does not necessarily have to improve but the ability to control and manage a complex and powerful tool has to improve. Just like flying, the best way to improve these skills is high quality practical training. Engineers will have to put in training environments where the tool is not working effectively to safely learn how to control it at the limits rather than learning whilst working on the job. Design automation is not therefore just a challenge in terms of the tool development but also in how we train engineers to operate the new design tools.

In developing this framework we wanted to demonstrate two things; firstly, that automated design can be undertaken using current technology. All the processes discussed here could easily be achieved using technology that is both relatively simple and mature and easily available. Artificial Intelligence is not needed to automate substantial parts of our doing processes for simple structures.

Secondly, to demonstrate it could be effective in improving efficiency - but it is not without challenges for the industry. With some effort up front, industry could embrace the modern wave of automated design to improve our design efficiency without having to wait for someone else to solve the problems for us.

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References

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“The biggest certified test tunnel in the world”
TODAY ALL TUNNELLING MODELS exist in 3D. This has traditionally had to be imported into the drilling jumbo or underground drill rig. This would then be used alongside such drilling software as Atlas Copco’s Underground Manager or Sandvik’s iSURE, with all the drill plans having to be done manually. A recent development, which was field tested in Norway, has led to improvements in underground tunnel drilling, as Atlas Copco’s new Dynamic Tunnelling Package enables the importing of the 3D tunnel model along with a set of ‘drilling-rules’.

The package works through a set of drilling rules and the 3D tunnel model being used simultaneously by the jumbo drill rig, which is connected by USB or Wi-Fi. The rig then makes its own drill plans based on it tunnel location. Due to this, the drill plans will always be precisely made for the section and size that should be excavated. In effect the software creates its own drill plans directly at the face of the tunnel producing tangible benefits for contractors, and vitally, anyone living in close proximity to any work.

“Today, in tunnelling projects, especially large ones in urban areas, there are differences in the cross section. You go up and down with your drill plans”, says Atlas Copco’s Johan Jonsson. “Our Dynamic Tunnelling Package helps users so they don’t have to go up and down anymore. The drill plan is made on the drill rig and at the face.”

The benefits of the Atlas Copco development were seen during the use of the package on its highly successful pilot project in Bode, Norway. Here the company Veidekke has been working on the construction of the state highway 80. This involved the construction of a two-lane 2.5km tunnel which required the excavation of 500,000 cubic meters of rock.

Jon-André Nilsen, Manager Surveying Technic Underground, Veidekke, commented, “The collaboration with Atlas Copco to develop the Dynamic Tunnelling Package went well. Atlas Copco was responsive to our feedback and made adjustments to the program. Today, the drill rig operators make niches manually. They can turn out way too big or way too small. The Dynamic Tunnelling Package makes our drilling more precise. We can make changes to drill plans directly on the rig. We can move cuts or drill-holes. We are more flexible at the tunnel face compared to making all changes at the office. We use the
Dynamic Tunnelling Package to make niches (areas of the tunnel with larger cross section). This makes the work more precise."

The new development has also been well received by those at the sharp end. "The Dynamic Tunnelling Package is very easy to use. It is two keystrokes and you are started. The contour turns out very accurate", said Kent Simensen, drill rig operator, Veidekke. "The end result is identical to the drawing. Dynamic Tunnelling Package has made my work in the tunnel a lot easier."

Effective developments
Finnish company Robit has developed a drilling system for top hammer drilling equipment that uses fibreglass grout-injection tubes instead of steel tubes. Showing the effectiveness of the development, the Robit drilling system has been successfully utilised on a railway tunnel in Switzerland, which faced serious risk of tunnel face collapse. In order to overcome this, the tunnel roof was reinforced with 159mm injected steel tubes (the Forepoling method), but the part to be excavated also had to be consolidated with 76mm fibre glass tubes. The 159mm steel tubes had a total length of 15m. The fibreglass tubes had to provide support for at least a further 8m after the tunnel advance, which meant that they had to be drilled a total length of 20-21m. Using a drilling jumbo and drilling horizontally, but with a small drill (76mm), this presented a real challenge to the drilling equipment. The new method was used to replace conventional self-drilling anchors, which proved to be unreliable, and did not comply with the project’s requirements for hole straightness (50cm in 20m). Robit’s equipment met this requirement, with the contractor, A.T.S. Infratunnel, reporting that the project, the first with this fibreglass bolting method in Europe, is now back on schedule whilst maintaining an excellent safety record.

Swedish company Brokk has seen some of its newly developed equipment use recently added power to find a ready niche within tunnelling. One such project has been on the Doha Metro in Qatar, with Brokk machines being used for excavation work in the cross passages. The equipment used were the B260 and B160 chosen due to their high power to weight ratios and ability to take on a number of different tasks on the project.

In order to speed up the production rate on the excavation work, a machine was placed at

A selection of Brokk robots working at a tunnel face.
SURFACE CHALLENGES – Underground solutions

Worldwide there is a quest for urban space driven by the increasing urbanization.

The challenges are numerous and availability of space for necessary infrastructure is crucial. The underground is at present only marginally utilized. The potential for extended and improved utilization is enormous.

“Surface challenges – Underground solutions” is more than a slogan; for ITA-AITES and its members it is a challenge and commitment to contribute to sustainable development.
either end of the cross passage, and then operated with the goal of meeting up in the middle. Progress has averaged about 25 cubic metres per day, with a relatively soft rock hardness of approximately 10-20MPA at this part of the metro. Nicolas Combe, Cross Passage Manager for Doha Metro Red-Line South says: “This is the first time I have been working with Brokk machines. I am really impressed with their flexibility. They are good machine and powerful to work in confined space.”

The project saw the use of six Brokk B160s, with four of them mounted with TEI-drilling rigs, breakers, scabblers and also shotcrete attachments. The procedure involved the Brokk robot equipped with a TEI-drill making approximately 40x75mm holes, with 9m depth to secure the cross passage. The estimated time to drill one hole was 15 minutes, with the hardness of the rock being as high as 120MPA. Following this stage, a breaker attachment was used for excavating through the rock or, in softer areas, a Brokk scabblower attachment. The Brokk machines were also used to trim the edges. A third step has been to shotcrete and secure the cross passage. The Boomer WE3C drill rigs themselves were also equipped with the COP4038 40kW rock drill. Implenia is a long standing customer of Atlas Copco’s, but the equipment was chosen due to the match between the cross section of the tunnel and the coverage provided by the drill rig. The rigs themselves were also equipped with Atlas Copco’s recently developed Dynamic Tunnelling Package.

Longest road tunnel
The E4 Stockholm bypass – Förbifart Stockholm – is a new route for the European highway (E4). The new link will connect the southern and northern parts of the Stockholm locale, relieve the arterial roads and the inner city of traffic thereby alleviating strain on Stockholm’s traffic system. The new link west of Stockholm has been under investigation for several decades, with a large number of alternate routes initially being considered. In order to reduce any impact on sensitive natural and cultural environments, just over 18km of the total of 21km of the road link are in tunnels.

The construction work of the three lane tunnel located in western Stockholm began in 2015, and will take approximately 10 years to complete. When the link opens for traffic it will be one of the longest road tunnels in the world. By 2035, the Swedish Transport Administration (Trafikverket) estimates that the Stockholm bypass will be used by approximately 140,000 vehicles each day.

One of the main contractors on the scheme is Norwegian company Implenia. Operational throughout Scandinavia, the company possesses many years of experience and expertise within complex infrastructure projects, specifically underground construction projects.

Such advanced technology on the Stockholm bypass came in the form of a selection of tunnelling jumbos and associated equipment from Atlas Copco. These comprised of Boomer WE3C drill rigs on site to excavate the main three lane tunnels, equipped with the COP4038 40kW rock drill. Implenia is a long standing customer of Atlas Copco’s, but the equipment was chosen due to the match between the cross section of the tunnel and the coverage provided by the drill rig. The rigs themselves were also equipped with Atlas Copco’s recently developed Dynamic Tunnelling Package.

Going jumbo in Acapulco
Weekend visitors to Acapulco Bay, Mexico, often fly into Juan N. Alvarez International Airport, which is situated in the Diamante zone of Acapulco. Upon landing, they haven’t really arrived as the Acapulco Bay beaches still are 12km away. This is soon to
change as Mexican company, Acatunel SA, is completing a 3.2km tunnel through the Cumbres de Llano Largo Mountain. The project began in 2013 when Guerrero state legislators allocated 3,500 million pesos ($213.4M US) for construction of what will be when complete the longest road tunnel in Mexico. When operational, this will provide a much shorter and quicker ride from the airport with the investment leading to the creation of hundreds of new jobs.

Acatunel SA de CV Consorcio ICA – Carso, successfully bid to drill the 3.2km tunnel through the Cumbres de Llano Largo Mountain, part of the rugged Sierra Madre del Sur range. Tunnelling runs from Cayaco on the south side of the mountain to Brisamar on the bay side.

To undertake this arduous project Acatunel engineers relied on Sandvik Mining and Rock Technology, specifically DT820-SC and DT1131-SC tunnelling jumbo’s to methodically punch through the mountain.

The ambitious nature of the project means that the sight of traffic flowing through the tunnel is at least half a year away, although the tunnel was ‘broken through’ in the summer of 2016. Acatunel work crews are still inside the mountain continuing to work in two 12 hour shifts a day. The tunnel progressed at about 7.2m each work day, although some days, the progress did not come easily as the Cumbres de Llano Largo geology proved to be less than perfect for tunnelling. The base of Cumbres de Llano Largo Mountain itself is comprised mostly of granite (made up of quartz, mica and felspar) and basalt.

These two abrasive and hard types of rock providing a challenge to any drill team and its equipment.

One particular problem that drillers encountered was the large amount of water which had to be collected and diverted. Some of the rock is riven with fractures, which led to collapses and landslides.

“What happens is that the ceiling of the tunnel falls in, leaving a hollow upper part over the tunnel,” says Miguel Angel Banuet Rodriguez, the project’s general supervisor. “This hollow space needs to be filled in with shotcrete or hydraulic concrete so as to make it safe. This causes delays.”

To meet the challenge where the drilling boom meets the rock, Acatunel mated Sandvik T38-Hex35-R32 16 foot rods, T38-T38 couplings and RD525 drifter shanks with 48mm bits.

Miguel Angel Banuet Rodriguez says the durability of the Sandvik drilling components has helped his crew hammer its way through the mountain. Acatunel has also utilized Sandvik DX680 and DX700 surface drill rigs to open the tunnel, and create benching for water drainage within the tunnel.

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Underground Construction professionals from around the world will gather in San Diego for the 2017 Rapid Excavation and Tunneling Conference (RETC).

This international forum will draw 1,500 industry experts from more than 30 countries to exchange ideas, build relationships and learn about the newest innovations and advancements in tunneling technology.

Don’t miss this fantastic opportunity to connect with peers, enhance your technical expertise, and promote your business to the tunneling industry’s key decision makers. Attendee registration is open, so sign up today!

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Sandvik DT912D intelligence

At CONEXPO/CONAGG Sandvik Mining and Rock Technology showcased the latest tunnelling jumbo in its extensive offering, the Sandvik DT912D. Designed especially for limestone applications, this new high reach - single boom jumbo is completely self-contained. It is powered with a fuel efficient and environmentally friendly Tier 4 Final diesel engine and equipped with onboard compressor and water-tank for air-mist flushing. With the new Intelligent, state-of-the-art control system it will bring to customers high quality and increased productivity in both tunneling and underground mine production.

Sandvik DT912D – a self-contained, air-mist flushing, diesel-hydraulic high reach single boom jumbo – offers high quality drilling in its most advanced form. Designed for fast and accurate drifting and production drilling of 12 to 125m² (130 to 1345 sq-ft) cross sections, the 24-ton jumbo combines the novel technology, creativity and expertise from Sandvik with the vast experience gained over the decades in the business. Being completely self-contained Sandvik DT912D is an optimal machine for multifaceted operations that will take excavation efficiency to another level.

Featuring a 25kW (33.5Hp) high frequency RD525 rock drill for superior drilling performance with high lifetime, as well as the most powerful engine ever installed on a diesel-hydraulic jumbo, the Cummins Tier 4 Final with 205kW (275Hp), the machine can bring a true boost to productivity with low fuel consumption. As a standard, the jumbo has an electric controlled drilling system with added automatic functions, including one-hole automatics and is equipped with a SB150 universal boom for large, optimally shaped coverage and full automatic parallelism. In addition to face drilling, the versatile boom can also be used for crosscutting, bolt-hole coverage and full automatic parallelism. In addition to face drilling, the electric controlled drilling system with added automatic functions, including one-hole automatics and is equipped with a SB150 universal boom for large, optimally shaped coverage and full automatic parallelism. In addition to face drilling, the versatile boom can also be used for crosscutting, bolt-hole coverage and full automatic parallelism.

Efficient 4m³ (141 cfm) onboard compressor and an extra-large 1000 liter (265 gallon) water tank for air-mist flushing allow Sandvik DT912D to operate independently from the tunnel or mine infrastructure and guarantee longer drilling period from one set up. This enhances the efficiency of the total cycle time and gives extra flexibility of use. Sandvik DT912D offers rapid, safe and balanced trampling thanks to its powerful, 4-wheel-drive center articulated carrier. Also the ITA tunnelling awards shortlisted, FOPS/ROPS complied cabin is ergonomically designed and well insulated to minimize noise and vibration; the noise level remaining under 73dB (A) at all times. As an option the cabin is also available with a cabin lifting system allowing even better visibility to trampling and drilling. This all makes the new jumbo an enjoyable workplace for the operator. Furthermore, the well-proven Sandvik Intelligent Control system Architecture (SICA) with comprehensive built-in diagnostics and user-friendly controls ensures ease of use and maintenance.

To ensure the best performance, Sandvik DT912D offers different instrumentation levels to choose from optimizing its performance in accordance with specific needs. These include the silver packages for drilling angles and depth monitoring, while the gold package offers semi-automatic drilling according to drill plan. The platinum package, being the most comprehensive one, has the advantage of automatic boom movements and drilling cycle. The gold and platinum packages are integrated with the Sandvik iSURE® tunnel management tool for accurate drilling, charging and blasting plans. In addition, the iSURE® provides useful data collection and analysis reports for improving the work cycle and process and can also be complemented with the new geoSURE rock mass analysis and visualization system.

Oslo protection

PassiveTec®'s innovative tunnel fire protection technology has been selected and installed for the renovation of Oslo’s Tåsen Tunnel.

To achieve a required 120 minutes fire protection (based on the RWS time/temperature curve), PassiveTec® fireboards have been applied as wall cladding in the tunnel. PassiveTec® XT intumescent sealant was used for the expansion/construction joints, together with Fischer FNA II A4 anchors and tunnel coating from Kapyfract AG.

PassiveTec® Tunnel Liner fireboards are made from fibre reinforced magnesium and other refractory products. As well as outstanding fire protection performance, these specialist boards are free of hazardous substances, offer excellent stability and durability under humid, wet or freezing conditions and are easy and quick to assemble.

To further increase the speed of installation on the Tåsen Tunnel project, made-to-measure panels were cut to size and coated off site. The 24mm PassiveTec® Tunnel Liner used in Tåsen Tunnel is also the thinnest and lightest globally RWS-rated board.

Atle Killerud, Technical Manager at specialist fire protection contractor Firesafe, said: “When PassiveTec boards were submitted and tested for use in both tunnel lanes they were found to match – and in most cases exceed – the specification requirements. “The boards are currently being installed the project completion on both lanes expected during the early part of 2017. The project was handled in a professional and efficient manner, with materials being delivered on time.”

Delivered by main contractor Peab Norway for Statens Vegvesen, the 250 million NOK Tåsen Tunnel project is part of a comprehensive national tunnel upgrading programme which will see more than 200 tunnels across Norway being upgraded by 2019. The upgrading works includes fire protection, new emergency exits and replacement of signalling and service equipment.

PassiveTec® director Simon MacDonald said: “We are naturally delighted that PassiveTec® Tunnel Liner was selected for this important city-centre infrastructure project.

“This contract again demonstrates that with its ability to achieve superior fire and insulation protection in harsh environments, PassiveTec® Tunnel Liner continues to set new standards for fire protection in tunnels.”
**Brokk introduces new power**

Brokk introduces the new Brokk 500 which features 40% more demolition power, the Brokk

**SmartPower™ electrical system,** a more powerful breaker, extended reach and industry-leading serviceability. And it adds a portion of good looks to the worksite as well.

The new Brokk 500 adds 40% more breaking power than its predecessor. The machine delivers 1,500 joules punch with each blow of the 700kg heavy Atlas Copco SB702 hydraulic breaker. On top of that it adds further length to Brokk's signature three-part arm system, now reaching 7.4m vertically and 7m horizontally, making it ideal for work where the extra reach is of importance. Still the Brokk 500 retains most of the compact proportions of its predecessor, the Brokk 400. With its 5,200kg it is only marginally heavier and the width of the machine is the same. And it is “backwards compatible”, so all the tools and attachments used for the Brokk 400 can also be used on the new Brokk 500.

**The Brokk 500 comes with**

- **SmartPower™ electrical system** – Brokk SmartPower™. This new smart electrical system is a key part in creating the performance improvement of the machine. It maximizes the power output of the machine at any given time, based on both environmental and operating factors. The Brokk SmartPower™ system is uniquely designed for the extremely tough operating environment of a demolition robot. Its components are either designed by or modified by Brokk to withstand the demolition forces over time. In addition it helps the operator to get the machine started on poor power supply, while at the same time it protects the Brokk machine from any harmful faulty power.

- **The Brokk 500 incorporates** the industry-leading reliability and serviceability that Brokk has become known for over the years. New on this machine is that operators now can complete all daily and weekly maintenance without even having to lift the covers of the machine. And replacing any damaged hydraulic hoses is now simpler than ever.

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**Normet and Aramine cooperation**

Effective immediately, Normet OY and Aramine SAS are pleased to jointly announce a cooperation in French speaking Africa for the distribution of equipment and after-market products, services and support. "We are delighted that Aramine, with their track record of success in the targeted countries and their customer-focused culture, have agreed to carry the Normet brand to their existing and new underground customers in this emerging territory" stated Mike Rispin, SVP Sales and Marketing for Normet Group. "Aramine’s representation of Normet in Morocco, Tunisia, Algeria, Niger, Burkina Faso, Sierra Leone, Chad, Senegal and Ivory Coast strengthens our offering to the underground mining and construction markets there, and augments our value proposition in the region" added Janne Lehto, Region VP for EMEA.

Distribution has always been an important activity for Aramine, with the main advantage being a complementary range to Aramine products, enabling the French company to offer a wide range of equipment with the right after-sale service through its divisions located close to the mining operations. Patrice Lepetit, Spare parts Sales Director says: "Brand partnerships totally complete Aramine activities and allow us to bring the perfect product among a wide range of choices to our customers."

The partnership agreement with the Finnish manufacturer Normet adds utility vehicles for underground mining and tunnelling to Aramine’s products panel. Xavier Domenach, Equipment Sales Director says "this range is a perfect complement to the Aramine products and will enable us to meet all the needs of our customers". A training program for Aramine technical teams is already scheduled to ensure the best service from the first days of this partnership.

The Aramine/Normet combination is not a first-time event. Aramine previously represented the brand and helped establish a Normet presence in the territory. "When the opportunity presented itself to rekindle a relationship with a world-class OEM supplier of underground utility equipment, we thought immediately of Normet" said Marc Melkonian, Co-President of Aramine. Negotiations proceeded systematically and effectively, culminating in the current agreement. Said Bruno Chivee, Normet’s territory Sales Manager: “Through discussions, it became increasingly apparent that this is a good three-way fit, and that Aramine and Normet and our mutual customers are once again associated in French Africa.”

Aramine begins now to market the Normet offering through its various organizations.
At VINCI Construction Grands Projets, we engineer digital solutions that help us and our Clients in the conception and construction of our major projects.

On SEA Tours-Bordeaux high speed rail line (302 km and 38 km of connecting track), we developed a bespoke information system allowing sharing of processes and data between all partners (80 design offices, 5 sub-consortiums, 3,500 employees) that offers the most reliable performance. We introduced an Electronic Document Management System (EDMS) and a Geographical Information System (GIS) whose 3D interface fostered collaboration with clients and stakeholders. This real Asset Information Management (AIM) is being transferred to the dedicated company for the maintenance of the project over 45 years.

In the UK, we are currently placing our BIM expertise at the core of infrastructure projects such as Tideway East and the M4 Corridor around Newport, with the aim of providing enhanced collaboration and efficiency.

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AUTOMATE DESIGN
A FRAMEWORK IS DESCRIBED THAT COULD BEGIN THE TREND FOR AUTOMATED DESIGN

DELIVERING IN DELHI

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GLENDOE REACTION
PROF ARNOLD DIX REVIEWS THE COURT’S GLENDOE COLLAPSE FINDINGS

SEE PAGE 23

SEE PAGE 52
DIFFICULT GROUND SOLUTIONS:
SPECIALIZED TBM IS KEY TO REVAMPING NEW YORK CITY’S WATER SUPPLY
Connecting Norway by rail: 5 Herrenknecht Hard Rock TBMs are on the move for **45 km of new first-class rail tubes** at the New Ulriken tunnel and Follo Line projects.

**Hard Rock**

Massive geologies call for experienced partners. Herrenknecht is making headway through hard rock – for over 822 km.

**Toughest**

Biting its way through the Scandinavian stone, the TBMs are facing the absolute **hardness test** when dealing with up to **350 MPa** rock strengths. Equipped with excavation tools for such a demanding mission, the Herrenknecht TBMs will complete all their tasks.

**Contractors:**
- Follo Line: Acciona Infraestructuras and Ghella ANS
- Ulriken tunnel: Skanska Strabag Ulriken ANS

Pioneering Underground Technologies

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Bertha’s back!

So finally, and with great and highly deserved celebration, Bertha has re-appeared, breaking into the fresh Seattle air completing her ‘eventful’ and most certainly challenging journey. And what a journey it’s been, with its ups and downs and probably a few sideways, but one thing is for sure, breakthrough will herald the start of not only the beautification of Seattle’s currently wasted sea front, but also the furious, unashamed back-peddling of a legion of ‘not in my back yards’!

There’s no point in pretending the project has not been without its problems, but that’s now something to be sorted out between the parties involved. What we do know is a 57.5ft diameter EPBM driven by a hardy team of tunneling engineers has delivered a fantastic piece of infrastructure, along with a rake of lessons to be learned to the betterment of the industry as a whole.

I’ve touched on this before, but it is worth repeating, with regard to the public perception of infrastructure projects such as the Alaskan Way Viaduct Replacement, the sheer beauty of the destination far outweighs the tribulations of the journey. In 10 years time when the good people of Seattle are immersed in the loveliness of their new opened up seafront, free from the scaring of the ugly Viaduct, do you really think they will still talk about Bertha’s main bearing issues? Very unlikely, but if they do, I truly believe it will be more through admiration, and also by way of thanks to the teams who struggled through adversity to give the city the environment it truly deserves.

So just consider, in 10 years, the teams who delivered the SR99 tunnel may well be causing another NIMBY group somewhere on this huge continent massive inconvenience whilst again delivering them something they actually need. But in Seattle’s the NIMBYs of today will probably be wondering how they ever lived without the tunnel they so vehemently protested against in the first place…

Great job to all involved, it’s definitely beer o’clock, and you deserve it!

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On April 04, Bertha, the SR-99 Alaskan Way Viaduct Replacement Scheme’s 57.5ft (17.52m) diameter Hitachi Zosen EPBM successfully completed its 1.7-mile (2.7km) long drive beneath Seattle, breaking through 64 years to the day since the viaduct first opened to traffic.

Led by the client, Washington State Department of Transportation (WSDOT), and the design and build contractor, Seattle Tunnel Partners (STP), the tunnel project will now move a two-mile section of SR-99 underground when it wraps up in early 2019. Crews will then demolish the viaduct, clearing the way for the city’s new waterfront.

“This is a historic moment in our state’s transportation history,” Gov. Jay Inslee said. “Innovation and perseverance are the engines that keep Washington in the forefront. There is still more work ahead but this moment is one worth celebrating.”

Crews will now remove steel support braces that stand between Bertha and the interior of the 90ft-deep disassembly pit. When the braces are gone, crews will drive the machine into its final position and begin cutting it into pieces for removal. As owner of the machine, the contractor will determine which pieces will be salvaged for use on other projects or recycled.

“We were always confident that we would successfully complete the tunnel drive,” STP Project Manager Chris Dixon said. “The dedication and commitment of everyone on the Seattle Tunnel Partners team has been exceptional, and we wouldn’t be at this milestone without the hard work of our crews. We look forward to continuing this outstanding progress through project completion.”

STP still has significant work to complete before the tunnel opens. Crews must finish building the double-deck highway within the tunnel, and mechanical and electrical systems, plumbing and safety features must also be installed.

Even as crews are installing these systems, crews will begin the extensive task of testing and commissioning the tunnel to ensure it’s ready for traffic. Inspectors will individually test more than 8,500 separate components before testing each of the tunnel’s various systems as a whole.

“This truly is a remarkable feat of engineering,” Transportation Secretary Roger Millar said. “There’s still work to be done, but the individuals working on this job should be proud of this accomplishment.”

Over the next several years, the City of Seattle’s Waterfront Seattle project will build new public space and a surface boulevard in the place of the double-deck viaduct, which is scheduled for demolition in 2019.

“Today is a major construction milestone in our plan to reclaim Seattle’s waterfront,” Seattle Mayor Ed Murray said. “We are one step closer to taking down the viaduct to make way for a reimagined waterfront and surrounding downtown neighborhood. We will build a waterfront for pedestrians, transit and sensible car trips without a freeway wall casting a shadow over our vision of a well-connected 21st century city.”

King County Metro will continue to rely on SR-99 to route buses to Seattle after the tunnel opens, said King County Executive Dow Constantine.

“The new tunnel will provide fast, reliable travel for transit and freight past downtown traffic, and reunite the city with its waterfront,” said Constantine. “The breakthrough highlights what we can accomplish when we think big, act boldly, and embrace the ‘can-do’ tradition of our region.”

Port of Seattle Commission Commissioner Courtney Gregoire said the tunnel will work with the new waterfront surface street to accommodate freight traffic.

“This Alaskan Way route is essential to a strong port and linking our industrial lands between SODO and Ballard,” Gregoire said. “Strong, vibrant transportation connections are essential to keep our economy growing and creating middle-class jobs.”

Manufactured in Japan by Hitachi Zosen, Bertha arrived in Seattle in April 2013. The machine was launched from a pit near the city’s stadiums in July of that year. In December 2013, STP stopped mining after measuring increased temperatures in the machine.

After an investigation, STP discovered damage to the machine’s main bearing. Crews completed repairs and resumed mining in December 2015. The cause of damage to the tunneling machine is in dispute and is currently in litigation.

Delegates attending this year’s Cutting Edge Conference – to be held in Seattle on November 13-15, 2017 – will be among the first ever visitors to journey through the completed tunnel as part of the conference’s site visit.
Crenshaw/LAX tunneling completed

On April 06, ‘Harriet’ Walsh-Shea Corridor Constructors (WSCC) JV’s 21.5ft diameter Herrenknecht TBM arrived at Leimert Park Station, completing the second of two 1-mile (1.6km) long tunnel drives that will connect Metro’s Crenshaw/LAX Transit Project’s three underground stations.

Named after Harriet Tubman – the abolitionist who freed slaves from the south via the Underground Railroad – the TBM commenced excavation at the future Crenshaw/Expo Station in April 2016. In August, the TBM reached Martin Luther King Jr. Station and then began excavating the last segment of the tunnel in September. By October 20th, she had arrived at Leimert Park Station completing her first drive.

Following disassembly and transportation back to the Expo construction yard, the TBM was lowered back underground and reassembled for the northbound drive, which began on November 29. The TBM excavated about 60ft per day and removed 144,250 cubic yards of soil for the second tunnel. A crew of 75 workers manned the machine over three shifts, five days per week.

Once complete, the 8.5-mile long Crenshaw/LAX Line will connect the Green and Expo lines with eight new stations to serve the Crenshaw, Inglewood, and LAX-adjacent communities. The project is projected to open in the fall of 2019.

A ninth station — separate from this project — will be added at Aviation Boulevard and 96th Streets. Crenshaw/LAX Line and Green Line riders will use that station to transfer to a people mover being built by LAX that will serve the airport terminals. The airport is aiming to have the people mover completed by 2023.

The $2.058 billion Crenshaw/LAX Transit Project is funded largely by Measure R, which was approved by Los Angeles County voters in 2008.

MTA OKs $492M Canarsie Tunnel repair contract

On April 03, New York City’s Metropolitan Transportation Authority (MTA) board approved a contract that aims to accelerate the rehabilitation of the L train’s Canarsie Tunnel, under the East River, by three months. The contract will also improve two stations, and build a station that will allow more trains to run on the L Line, increasing capacity.

The $492 million contract with Judlau Constructors (WSCC) JV’s 21.5ft diameter Herrenknecht TBM arrived at Leimert Park Station, completing the second of two 1-mile (1.6km) long tunnel drives that will connect Metro’s Crenshaw/LAX Transit Project’s three underground stations.

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Fort Wayne CSO awarded

Salini Impregilo and Lane Construction Corporation (Salini Impregilo Group), through its wholly owned subsidiary S.A. Healy Company, have won a $188 million design-build contract for the Three Rivers Protection & Overflow Reduction Tunnel (3RPORT) combined sewer overflow (CSO) tunnel project located in Fort Wayne, Indiana.

On February 15, Ft. Wayne (Indiana) City Utilities publicly opened bids for the estimated $250 million project. Five pre-qualified joint ventures entered bids, they were: S.A. Healy/Salini Impregilo at $187,963,000; Shea/Jay Dee at $205,998,194; Strabag/Walsh at $224,983,000; Taylor/McNally at $225,694,734; and Kiewit/SELI at $229,889,934.

The tunnel is part of Fort Wayne’s agreement with the federal government to reduce the amount of CSO that is currently being discharged into rivers during wet weather.

The 3RPORT CSO includes a deep rock tunnel, drop shafts and consolidation sewers to collect and convey CSO from eight locations along the St. Mary and Maumee Rivers. Once completed, the CSO tunnel system will reduce 90% of combined sewage overflows into the rivers, which occur during large rain storms.

The tunnel will begin south of Foster Park on the east side of the St. Marys River. It will run parallel to the St. Marys River, cross Swinney Park, go through downtown then run parallel to the Maumee River until it reaches the existing sewage treatment plant, which is located on the Maumee River east of North Anthony Boulevard.

The 3RPORT CSO tunnel project is Salini Impregilo and S.A. Healy’s fourth in the United States. They are working on the Anaostacia River Tunnel project in Washington, DC, along with Parsons Construction Group; as well as the Dugway Storage Tunnel project in Cleveland, Ohio. Previous work includes the West Side CSO project in Portland, Oregon. Salini Impregilo and S.A. Healy have worked together on six completed or ongoing projects totaling over 20 miles of bored tunnels.

Construction on the 3RPORT project could begin in late May or early June and be completed by mid-2021.
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SEEKING PATIENCE!

IT IS SAID THAT patience is a virtue. It is however, a virtue that I struggle with. I’ve never been very good at waiting for things, preferring a swift resolution of issues and problems with a straightforward conversation – preferably face-to-face. Yes, my apologies for being so old-fashioned that texts and emails just don’t do it for the big conversations. It is the reason that we travel to talk to clients, the reason we gather for conferences, and the reason we meet with our dispute review board members. Don’t get me wrong, email is great, but seeing a facial reaction to a discussion point and being able to immediately sense the mood of the room, detecting when something is misunderstood or offensive, is priceless.

There are times in every project when waiting around for the next step is normal. I have been part of many meetings where we are discussing what milestones and processes in the life of a project are most likely to see schedule lost. Among the usual suspects of TBM interventions and more cutting tool wear than expected were a few other issues that warrant some thought and have potential for improvement.

Problems are always expected in major underground projects. When it comes to schedule delay, the combination of linear construction and the major hazards we deal with that are directly related to excavation and support, lead to almost inevitable delay. This delay occurs with reference to the optimistic schedule that a low bidder must make in order to win the job. Catching up on an optimistic linear schedule becomes almost impossible.

Unfortunately, the low bidder often begins the project in the hole of delay due to early issues during setup of the contract and setup of the site. It is clear to everybody that purchase and manufacture of a TBM takes a year or more and that many other work items are needed and completed to enable TBM launch. This schedule is well understood and reasonably reliable. The startup phase of TBM tunneling, however, is rarely accounted for objectively and is rife with optimistic assumptions related to operation learning curve and TBM system troubleshooting. This kind of optimism puts tunneling behind the eight ball almost from day one – never to recover.

Overall project schedule delay, however, is most frequently lost before the contractor ever gets on the job. Two processes are most guilty for delays: the procurement phase, and the time period between Award and Notice to Proceed (NTP). Procurement is always a nerve-wracking time for everybody involved. Contractors are putting themselves on the line to bid work and taking serious commercial and reputational risk in the process. Owners are wondering whether they will soon be embarking on a major underground project with a good price that fits their allocated budget or whether they will be delayed and explaining to senior management why the budget was blown by a higher than expected bid price. Engineers are nervous because they will face the reality of questions about their design and they feel the burden of setting a budget that they really hope will fit with the bid price. Coupled with this, Engineers also face the reputational impact of their design and estimate being deemed good.

Regular design bid build procurement experiences frequent delay getting the bid documents through final approval and out on the street; delay in getting questions answered; and ultimately a postponement of the bid date. But this type of delay is typically insignificant when compared to what has become a “normal” US design build procurement. “Design build saves on cost and schedule” is the mantra heard time and time again from proponents of alternative delivery but this has become a fallacy in practice.

Cost saving innovation is suppressed by highly detailed reference designs and extensive design reviews. Schedule savings are wiped away during a reference design, tender design (within the total length of procurement), and then detailed design process that takes many times longer than a conventional design bid build design would take. In terms of overall procurement process, there can be no doubt that conventional design bid build in the US is a substantially quicker means to get to start of tunnel construction.

The new kid on the block that has great relevance to this conversation is “progressive” design build. This is where a bare framework of performance requirements is put forth and bids are requested that encourage innovation and cost savings. Progressive design build (or as the rest of the world would call it - “design bid build”) appears to be significantly swifter than the 18+ months that we see in US design build procurement. Progressive design build seeks to re-affirm the innovation, cost and schedule savings that should be at the heart of alternative delivery. It will be interesting to watch how this process works in practice and what benefits it will bring to upcoming tunnel projects in San Jose and Atlanta. I’m sure the less patient among us can’t wait, and I for one encourage this innovation.

After bid day, the time period between Award of contract and NTP can feel like forever. There is a natural excitement around the team upon being awarded a project. There are congratulations, dinners and other celebrations that precede a process of final negotiations, preparations and good old-fashioned waiting. The good feelings dissipate with time and still the team waits while the Owner goes through legal and contractual processes to issue the NTP. These are times where patience can be tested but what can be done?

It is often perceived that these delays are unavoidable but this is not necessarily so. Delays during procurement should be considered as avoidable as any other design or construction delay. We work so hard to reduce and eliminate inefficiency in our own processes. Must we simply be satisfied with inefficiency during procurement? Yes, sufficient time must be allocated for procurement and contractual administration, but why tolerate the delays? It is not uncommon for the scheduled start of construction to slip by several weeks or months due to delays at this stage.

My own form of impatience hates to see valuable time and effort wasted unnecessarily. We are always seeking to improve ourselves. That is why we come to work every day. By working patiently with owners we can improve procurement processes in our industry. There are those that will say this is a waste of time. But I have no patience for that kind of attitude!
As the TBM was poised to begin its journey along the Dugway Storage Tunnel in Ohio, we caught up with the owner, contractor and designer to find out about progress so far. By Kristina Smith.

**As the TBM was poised to begin its journey along the Dugway Storage Tunnel in Ohio, we caught up with the owner, contractor and designer to find out about progress so far. By Kristina Smith.**

**FIGURE 1 – Map of the whole system**

**Digging in AT DUGWAY**

**Digging in**

**AT DUGWAY**

**There are** A lot of similarities between Ohio’s Euclid Creek Tunnel and the Dugway Storage Tunnel, not least because they feed the same deep pump station. They are the same diameter, constructed through the same geology, with segments from the same supplier and they will even have been bored using the same Herrenknecht TBM and much of the same labor force and subcontractors.

With the Euclid Creek Tunnel successfully completed, it should be smooth sailing then for contractor Impregilo-Salini-Healy JV, which is around 40% through the construction of the Dugway. But of course, where Mother Earth is involved in the proceedings, there is no such thing as smooth sailing.

When the TBM begins its (2.8 mile) 4.5km journey at the end of April, it will be leaving 10 months later than initially planned due to difficulties in sinking the starter shaft.

“Most of the challenges and difficulties we were facing we have overcome,” says Jim Kabat, project manager for the Salini-Impregilo-Healy JV. “Now we are moving into the final phase which is mining the tunnel. There are some uncertainties related to that, but everything else has been dealt with.”

Dugway is the second of eight tunnel...
projects which make up NEORSD’s $3bn, 25-year Project Clean Lake program which began in 2011. The program will allow the District to meet Clean Water Act regulations by creating a network of storage tunnels to hold the combined flows after rainfall events and deep tunnel dewatering pump stations to convey the flows to the recently upgraded wastewater treatment plant; Euclid Creek and Dugway between them will be capable of storing 117M gallons of wastewater.

Currently when combined sewers fill up following rainfall, they overflow either directly into Lake Erie or one of the many creeks that terminate in Lake Erie. An estimated 4.5 billion gallons of combined sewer overflow flows into the Great Lake each year, harming the environment and sometimes making the beaches unusable for a while. Once Project Clean Lake is complete, the annual volume will be reduced to less than 500M gallons.

NEORSD awarded the $153.4M contract for Dugway to the Salini-Impregilo-Healy JV in November 2014. The winning bid was significantly below the Engineer’s estimate of $179M. McNally-Kiewit JV, who constructed the Euclid Creek Tunnel put in a bid of $170M.

The project was procured under a traditional form of contract: “We chose design-bid-build, based on the governing rules of our organization, and the amount of geotechnical, flow monitoring, property acquisition and hydraulic design work required,” says Doug Lopata of NEORSD. “The biggest design challenges were meeting our consent decree dates and CSO requirements and avoiding large claims by identifying and investigating all the major risk items.”

Lessons learned from the Euclid Creek

<table>
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<th>Tunnel Name</th>
<th>Length (ft)</th>
<th>Width (ft)</th>
<th>Bid Year</th>
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<td>24</td>
<td>2011</td>
<td>Complete - awaiting flow input</td>
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<td>18</td>
<td>2029</td>
<td>Advanced Planned - Design NTP in 2027</td>
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Source: NEORSD
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PRECISION IN PILING

Secant piles drilled to depths in excess of 120 feet creating a water-tight shaft for the Dugway CSO project in Cleveland, Ohio.
Tunnel project included the “early identification of utilities to allow for coordination for relocation or avoidance if possible,” says Lopata.

**Story of the shafts**

As well the 24ft (7.3m) ID tunnel itself, Salini-Impregilo-Healy’s package includes the construction of six shafts. At either end of the alignment are two 50ft (15m)-diameter shafts for launching and retrieving the TBM. Between those two points are four further 30ft (9m)-diameter shafts that will convey the flows from existing CSOs into the new tunnel via baffle drop structures; these shafts connect to the main tunnel via adits of varying lengths (see plan).

The three shafts at the Northern end of the alignment are all just over 200ft (60m) deep, whereas those towards the Southern end are deeper, up to 250ft (76m) for the retrieval shaft. However, whereas at the first shaft location (DST-1), there is 95ft (29m) of soft ground above the shale rock, at the most Southerly shaft (DST-8) there is just 15ft (5m).

The soft ground, below a layer of fill material, is made up mostly of clay, silty clay and clayey silt. However, within this are bands of material containing silt, sandy silt, gravelly silt and clayey silt, which behave differently to the main body of material. Triad Engineering and Contracting constructed three of the four intermediate shafts using steel liner plates and ribs through the soft ground, switching to a vertical boring machine to excavate the rock. The fourth shaft (DST-4) required a deep secant piled wall to provide the temporary support. Nicholson Construction installed the secant shaft, together with combined continuous flight auger (CFA) piles and cased secant pile walls to form gate structures around 50ft (15m) deep next to shafts DST-4 and DST-5 (see box).

Marra Services constructed shaft DST-8, where there was little soft ground, using excavators equipped with large hydraulic breakers. “It was a slow method, but a proven method and it worked very well,” says Kabat.

By mid-March, two shafts had their final linings in place and final linings for three more were under construction. Triad had excavated all the adits, which range in length from 10ft (3m) to 800ft (243m), using a simple 12ft (3.7m) TBM. All have finished a short distance from the line of the main tunnel, with the breakthroughs to be made after the main tunnel has been mined.

While construction of most of the shafts went reasonably well, the launch shaft was the one that caused problems. The plan had been to excavate the soil portion using steel ribs and liner plate for support, in conjunction with a vacuum-assisted dewatering system. The dewatering system was targeted to a band of cohesionless silt containing pressurized groundwater.

Salini-Impregilo-Healy attempted several methods of ground water control at the starter shaft, including installing internal vacuum wells and external grouting including jet grouting and permeation grouting. When none of these were successful, the contractor turned to ground freezing.

Geotechnical specialist Moretrench installed a row of refrigeration pipes around the perimeter of the shaft at around 3ft (1m) centres into the bedrock. One concern was that the pressure exerted by the expanded soil due to ground-freezing would cause problems with the steel ribs and liner plates already installed to support the shaft. Calculations revealed that some of the lower ribs would be loaded beyond their design capacity.

“We did some modifications to the ribs in places to strengthen them and we also installed strain gauges on the ribs and load cells behind the liner plates to monitor what was happening during the ground freezing,” says Kabat. “Once we had excavated through the water bearing silt materials, we poured a concrete collar around that area to ensure that everything would remain stable.”

Once through the soil, Salini-Impregilo -
Ground conditions at one of the shaft locations, DST-4, called for a different system of temporary support. Rather than the steel lagging and ribs, the designers specified a cased secant piled wall.

With a high water table, and piles that had to extend over 120ft (37m) before they reached the bedrock, achieving the required verticality was important.

"Nearer the bottom of the shaft there was a 10 to 15 foot sand layer and the water table was 12 feet down from the surface, so we had 100 feet of water head in that sand layer," says John Wise, vice president, operations, at piling works contractor Nicholson Construction. "Had we had any deviation between the piles, we would have had big problems with inflow of water."

The required verticality on the cased secant piles was 0.50% which is standard for this type of pile; secant piles were selected because they achieve better verticality than continuous flight auger (CFA) piles. Each of the secondary piles has three inch tubes cast into them so that grout could be injected at the pile/rock interface if there were any leaks observed—though these have not been used.

Nicholson employed a PRAD sensor from specialist supplier Jean Lutz which, attaches to the casing and tracks the average deviation of the piles, communicating via Bluetooth technology. These results were confirmed with a traditional Koden survey. Nicholson project manager Eugene Mirsky took the output from the PRAD and fed it into Google Sketchup to get a 3D image of exactly where the piles were.

“We started doing the 3D drawings on our last tunnel project in Miami,” says Mirsky. “It’s a good way of visualizing what is actually out on site, in order to report to the client or to find out if there are any potential issues. If we do all the checking before we excavate, we can remediate in advance.” In this case, the 3D sketch told Nicholson that all was well.

The other vital element of deep piles is getting the mix right. “When you are pouring concrete to 122 feet, you really have to pay attention and design your concrete mix so that it does not bleed,” says Wise. “A concrete bleeding under its own weight can create all sorts of problems.”

As well as a thorough mix-design and testing process before the start on site, Nicholson carried out Bauer Bleed tests and slump tests before any concrete was pumped into the casings. Specialist admixtures helped reduce the bleed of the 4000psi concrete.

Because of the depth of the 4ft (1200mm)-diameter piles, Nicholson employed an oscillator rather than the piling rig to pull out the casings. This worked well, but did add to the congestion of the limited working area.

“The biggest challenges on this project were sequencing and logistics,” says Mirsky. “It’s in an urban environment, so there wasn’t much room for storage, especially when the casings start to stack up or you’ve got six concrete trucks on site. It was difficult to maneuver three pieces of equipment – the rig, the crane and the oscillator – on one tight site.”

The condition of the working platform also proved difficult, says Wise. The ground was wet and the specification called for the use of slippery drilling polymer in the piles. “We had a lot of rain, we were drilling through clay material and using polymer, so things were messy,” says Wise. “We had to spend a lot of time maintaining our working platform to keep it in a safe condition.”

As well as the shaft, which will house a baffle drop structure to carry wastewater flows down to the main tunnel, Nicholson also constructed two gate structures at the DST-4 and DST-5 shaft locations that regulate existing flows to the baffle shaft. These are much shallower structures, around 65 to 70 feet (19.8 – 21.3m) deep, constructed with 3.2ft (990mm)-diameter CFA primary piles and 2.9ft (880mm) cased secondary piles. Nicholson carried out the work in the second half of last year, completing all the piling by the third week in December. Now that the shaft has been fully excavated, and the secondary lining is well underway, it’s safe to say that Nicholson’s 3D prediction of a leak free shaft was correct.

“They did a good job,” confirms Salini-Impregilo-Healy project manager Jim Kabat. “As far as I am concerned, those piles were completely dry.”

Healy used conventional drill and blast to excavate down to 6 feet (2m) below the springline of the tunnel. The construction of the starter and tail tunnel followed.

“We excavated the top heading for 130 feet in each direction for the starter and tail tunnels and then blasted the bench down to the final invert level of the tunnel,” explains Kabat.

**TBM modifications**

Having purchased the 27ft (8.2m)-diameter single shield Herrenknecht machine from McNally-Keiwit, Salini-Impregilo-Healy refurbished it on the job site. As well as a general once-over, the contractor made a few minor modifications which it hopes will aid the smooth-running of the tunneling process.

An extra grease pump was added to supply grease to gaps between the brush seals whose job it is to prevent grout running into the machine. “We want to makes sure we can fill the voids with grease,” says Kabat.
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Tunneling Fundamentals, Practice and Innovations
September 18-21, 2017

This short course covers emerging innovations in tunneling methods, materials and technology with instruction on key principles of design and construction in all ground types and across all excavation methods. Designed for industry professionals including owners, planners, designers, contractors, consultants and suppliers involved in the planning and construction of underground, tunneling and mining projects. Space is limited.

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“We understand there was some grout coming into the machine from the tunnel (on Euclid Creek), so we want to prevent that.” Other changes include new components such as the grout pump. “There are a lot of little things that we hope will increase reliability and make things work better,” says Kabat.

A modification aimed to assist with the quality of the ring build is the addition of guide rods to the radial joints. “Some believe that this improves the chances for improved ring build quality,” says Mike Vitale, tunnel designer for the MWH/Mott MacDonald JV.

“We are comfortable with guide rods because we’ve used them on our last two projects, one in DC and one in Portland,” says Kabat. “It does require you to be a little bit more careful as you are installing the keystone piece because you have got the guide rod sticking out as you are setting the piece, but it does help hold the shape.”

The guide rods are the only change to the segments, which are reinforced with Dramix steel fibers from Bekaert-Maccaferri and supplied by CSI Hanson (now Forterra). Attention to ring-build quality is more important with fiber reinforcement versus traditional rebar, says Vitale:

“Without a rebar cage, the segments are much more susceptible to cracking due to poor ring build. Attention to ring build is critical. If the build starts to suffer, and/or the ring is allowed to ‘squat,’ cracking can occur. If the leading face of the ring goes out of plane, tension cracks become apparent on the stones at all high spots on the leading face of the ring.”

“I have seen this in many fiber-reinforced segment tunnels and it is easily explainable, but people tend to deny the cause or blame it on other unrelated factors. When this occurs, careful and gradual packing of the joints can help correct the planarity of the leading edge of the ring, but ultimately, good ring build and prevention of squatting is the best cure.”

The most important factor in preventing ovaling or squatting of the ring is getting the grout right. As this is a rock tunnel, the void outside the segments must be immediately filled with rapid-gel grout, otherwise the springline moves outward and the crown comes down, resulting in the fore-mentioned cracking and ‘out of plane’ condition. The Euclid Creek Tunnel proved that it was possible to grout a segmental lining through the tail-skin of an open-faced rock TBM, which hadn’t been done before.

“Using an open shield in a rock tunnel made the set time and strength of the grout critically important. We knew that going in, but we were able to fine-tune these properties with the contractor by modifying the mix design during construction,” says Vitale. “Quality assurance and quality control vigilance was required. Also, McNally-Kiewit found that the mix design itself was not enough: the order the materials were placed in the batch as well as mixing time and mixing equipment all played a role in the success of the grout mix and placement.”

BASF, who supplied the grout and specialist input on the Euclid Creek Tunnel, is doing the same on the Dugway. However Salini-Im pregilo-Healy has not chosen to copy exactly the mix used on the previous job.

“We went through six months of testing to confirm gel times, set times, flowability characteristics, all of the things you need to get right,” says Kabat. “The biggest thing is to ensure we had flowability to fill the void completely as the machine is moving forward, but also to get the initial set.”

When asked what the biggest remaining uncertainty is, Kabat pinpoints the grout. “We will need to do some fine tuning to ensure that the operation runs smoothly,” he says. “The grout is the key component in this whole system. We will have the grouting consultants on site to make any required modifications.”

The other potential risk is methane. This ground is classed as potentially gassy. “We have encountered gas in all the shafts; one was shut down for around a month to allow it to vent,” says Kabat.

In the tunnel itself, the ventilation system has been designed to deal with any potential gas. “We anticipate that if we do hit any gas, the ventilation system will dispense it so quickly that we may not even be aware of it,” says Kabat.

Should the miners encounter a concentration of gas above 20% of the explosion limit, everything but the ventilation system will shut down; there is contingency in the contract for this.

**Big lifts**

Having refurbished and assembled the TBM on the surface, Salini-Impregilo-Healy decided that it made sense to lower the machine down in as few sections as possible. Ohio firm PSC Crane & Rigging is carrying out the lifting and assembly process using a gantry system with strand jacks.

PSC lifted down the 45-tonne main body in one piece and the entire 170 tonne cutter head. The contractor is using a system of slides to move the main body of the machine backwards and forwards while it installs the tail shield and ring erector.

As NATJ went to press, tunneling was due to start on 24 April. After an initial mining run of around 50 feet (15m) additional backup will be installed; another stop at around 200 feet (60m) in will allow the full backup to be put in place. Muck will be carried along the tunnel and up to the surface by means of continuous horizontal and vertical conveyors, supplied by H+E Logistik.

Hole-through is expected at the end of January 2018. Compared to the Euclid Creek Tunnel which took 14 months to mine 5.5km, nine months for the 4.5km Dugway would be a speedier drive.
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IN THE EARLY years of tunnel construction, water intrusion and subsidence due to ground loss were problems that were begrudgingly accepted as a consequence to the construction. Observations by Ralph Peck, during construction of the Chicago tunnel in the 1940’s, noted through observational techniques that settlements at the ground surface could be correlated to tunnel construction below. It was common to experience lateral movement and ground loss associated with the tunnel construction that could easily result in surface settlements on the order of twelve inches or more in a soft ground tunnel.

As the progressive tunneling industry sought methods to reduce settlement magnitudes resulting from tunnel construction, owners pursued remedies that would regain the trust of the public. Chemical grouting and early forms of compensation grouting were introduced with moderate success in the 1960’s and 1970’s. This was an attempt to remedy these issues. Other advances in response to these maladies included the creation of TBMs. Each successive generation of boring machine improved performance considerably from its predecessor. In fact, the performance has become so good with the latest TBM systems that some are asking: “Is the TBM alone enough?”

Open to debate
This very question was the subject of a panel discussion at the 2016 Cutting Edge Tunneling Conference in Los Angeles, California organized by NATJ and SME. The speaker panel of industry leaders consisted of; a Geotechnical Specialty Contractor (the author of this article), a Prime Tunneling Contractor, a Professor with a long career observing structure damage as a result of ground movement, and a Specialist Engineering firm who uses electronic instruments to measure movements resulting from construction activities.

The topic generated a lively discussion amongst the panelists and audience as well. While there was a considerable discussion, there was not a general consensus on the answer to the question. This is due to its difficulty to achieve agreement based on generalities that are associated with tunnel

construction. There are many variables that make a significant difference in the success of a tunnel being completed without causing damage to surrounding structures and utilities. A few of the variables that play a role in the outcome of ground performance resulting from tunnel construction include:

- The subsurface soil profile
- The type of the Tunnel Boring Machine selected for the project
- The care of the Tunneling Contractor advancing their shield
- The diameter of the tunnel
- The back grouting of the tunnel liner
- The type of structure that is being protected (a historic masonry structure is much less forgiving in terms of movement than a wood-framed, steel framed, or reinforced concrete framed structure)
- The condition and the type of subsurface utilities lying between the tunnel and the surface (a century old clay tile sewer is much more likely to have damage than a relatively new bell and spigot PVC sewer line)
- The depth of the tunnel below any of the

Jeffrey Hill PE, Director of Business Development for Hayward Baker looks at various risks associated with tunneling and asks the question – Is the TBM alone enough?
items referenced above
- The proximity to surrounding properties and relationship with the owner(s) of the surrounding properties.

It is really no surprise that the group of over 100 tunneling professionals could not come to a consensus, especially considering the wide variation in experiences and backgrounds of the panel members and the audience. Interestingly, one comment posed, since it is possible that if a tunnel could be completed perfectly without unforeseen conditions, then using a TBM alone is enough. However, the experiences shared at the meeting indicated that it would be a mistake to not be prepared for movement and rapid response mitigation.

A risky business?
While all types of construction entail certain degrees of risk, by its very nature, tunneling nears the top of the list in risk potential since nearly all of the work is completed “in the blind.” Even with extensive subsurface investigations performed in advance, the inherent variations in subsurface conditions leaves a significant element of the unknown. Therefore, the prudent approach to a tunneling project involves investigation of historical performances as well as the physical investigation of the subsurface materials as fundamental components of a risk mitigation plan.

The list of risk components shared by the audience was extensive. The more common elements itemized during the discussion included:
- Movement of earth or water into an excavation
- Excessive movement at the surface
- Gas infiltration into the tunnel, during mining or after the completion
- Differing below grade conditions
- Human error or mechanical malfunction of the TBM
- Litigation and Public Opinion

It is worth a more detailed discussion of the litigation and public opinion category. While many of the tunneling risks have remained fairly constant over the years, and even improved, public opinion and expectations of the public are constantly changing. As each successive tunneling project improves ancillary ground response, the expectations of the public and the owners are increasing. Further, the more litigious nature of today’s society places more scrutiny in regard to movements that will be tolerated.

The general public and adjacent stake holders of a tunneling project expect the project to be completed without being noticed by the public; let alone unwanted movement of the earth’s surface. As the TBM and the tunneling contractors have gotten better at preventing ground movement, the acceptable amount of movement is constantly being lowered as well.

This could be compared to something outside of our industry such as the average fuel economy of the vehicles traveling on the roads in North America. As fuel economy has improved, the public expects better fuel economy. Just as there is pressure on the automotive industry for constant improvement, there is pressure on the Tunneling industry for constant improvement as well. Therefore, the preparedness for Risk Mitigation has become a key element in modern tunnel construction. One form of risk mitigation is by contract.

There are various project delivery methods used in current practice around the world. Different delivery methods may result in a given owner having shed their risk to the contractor communities. Sharing of the risks on the project, or in some cases the owner retaining all risk, allows for more competitive bidding.

If a project is inherently too great of risk for the contracting community, the owner may find that they must carry more of the risk than on less difficult projects. This sharing of risk can be illustrated by owners selecting contractors for very difficult projects in other ways than the traditional Design and Low Bid. These alternative contracting methods can include selective design build. This technique allows contracting teams to be judged on technical merit as well as price. These alternative delivery strategies allow owners to select the team who has evaluated the risk for the

Compensation grouting crews are standing by as a large diameter TBM is set to launch for a subway tunnel in soft clays. The compensation grouting is intended to protect 3rd party stake holders.
After years of planning, design and ancillary construction, a large Diameter TBM is getting set to launch beneath an urban street.


date that tolerance for risk is in alignment with the owner’s.

Contractually, the owner can look at four alternatives for the mitigation of the risk of movement. The simplest case would be for the owner to rely on the means and methods determined by the prime contractor. The prime contractor may choose to mitigate their risks by including a specialist contractor. Generally, due to initial considerations for direct project cost, there is a high likelihood that the majority of tunneling contractors will begin tunnel work hoping for the best. In this case the owner has mitigated their risk by passing the risk to the prime contractor.

The owner can partially mitigate their risks on the project by specifying a real time electronic monitoring program for the tunnel project. The owner would generally specify allowable movement tolerances; still relying on the means and methods of the tunneling contractor to support the tunnel. However, now the owner and contractor learn in real time that movement is occurring. The contractor can then use this information to change their excavation and backfilling procedures to reduce movement, or even stop the excavation if needed, allowing for corrective measures.

The most proactive means, and perhaps closest to full mitigation of the risk, would be for the owner to specify the use of specialty geotechnical construction techniques to reduce the risk of unwanted movement as the construction progresses. In this case the owner is directly paying for a technique, such as jet grouting or compensation grouting, along with real time monitoring. Use of these specialty techniques by qualified specialist constructors has generally resulted in a reduction in movement, and therefore risk.

When the TBM performs as anticipated, the costs associated with specialty grouting programs may seem excessive. The project team can evaluate the risks with the tunnel they are to construct. If ground loss or movement can be tolerated, then there is a little reason to include a grouting program. However, if the owner’s public image cannot be tarnished through a bitter relationship with another project stakeholder, then the cost of the grouting program becomes inconsequential. Costs in this sense are not just measured in dollars. These costs can include delays to the completion of the project. Loss of goodwill with the public, and even political turmoil for future public funding.

Unlikely, yet real risks
As discussed above tunnel work stoppages can occur from differing site conditions. One very unlikely differing site condition can be caused by the inflow of hydrogen sulfide into the tunnel alignment. Due to the possible risk to human life, the tunneling program must be stopped until a grouting program can be implemented from the surface. If there is not a specialist contractor on site, there will be delays in contracting work, mobilization, design, testing of the grouting program, and executing the grouting program.

The owner knows of two modern tunneling programs that have been affected by the inflow of Hydrogen Sulfide. The first near Detroit, Michigan where a tunnel boring machine is still stuck in this unfinished tunnel. The second tunnel with H2SO4 issues is in St Louis, Missouri. The H2SO4 flowed into the tunnel through a probe hole causing unsafe levels of gas to be reached very quickly. This resulted in an evacuation of the tunnel and stopping the TBM. A grouting program from the surface was determined to be the safest manner to seal the rock formation that was producing the H2SO4.

The grouting program could only be started once access roads were cleared through a private wooded area. The property owner was less than pleased that his woodland was being cut back to allow for the grouting program. Completing a double row of rock grouting to a depth of 165 feet along an alignment of nearly 3000 lineal feet of tunnel is a significant effort. Despite working double shifts with multiple rigs the work still delayed the tunnel construction by several months. These delays created additional costs to the owner, and the tunneling contractor. The completion of the tunnel was also delayed, which in turn stressed relationships with the owner and the public.

On the alternative, the Author’s firm has been involved with a variety of tunneling projects in which specialist techniques have been specified by the owners. Historically owners in Europe and Asia have been more likely to mitigate risks by specifying specialty geotechnical techniques and monitoring. Aside from contractually mitigating risks from the beginning of the project the overall cost to the owner for the project is also reduced.

When completing the ground improvement program in normal work windows, with a longer bidding and procurement cycle, the costs, both direct and indirect of this program are more cost effective than the illustration included previously. Several projects in Europe and Asia can be used as successful case histories of very complex work being completed beneath settlement sensitive structures. The Crossrail project is perhaps the most complete example. However, this project has several successful predecessors over the previous decade including the Rome Metro and Central Train Station in Copenhagen.

In the last several years some owners in the United States have also looked to mitigate their risks contractually. This can be demonstrated by several successful soft ground tunneling projects completed by LA Metro. LA Metro was recently given a nod of approval in their handling of risk by the public – when the recent bond measure passed. Providing funding for future tunnels and light rail projects.

Final comments
The tunnel construction industry will continue to be full of both obvious and unforeseen risks. The proper use of specialty geotechnical construction techniques and real time instrumentation will keep this risk in check and allow it to be mitigated. Once the construction risks are mitigated, the public will once again gain trust in the competent experts that spend a career working on below ground structures. Mitigation of risks will also result in less litigation in our industry.
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EVERY TWO YEARS, industry leaders and practitioners from around the world gather at the Rapid Excavation and Tunneling Conference (RETC) in the US to learn about the most recent advances and breakthroughs in this unique field of ours. The comprehensive conference promises to help practicing professionals keep up with the ever changing and swiftly growing tunneling industry. Here you can put yourself in pole position to stay on top of new trends and technologies as well as innovative concepts, new equipment, materials, management, financing, and design challenges.

This year the event will see 21 technical sessions presented over the course of the three days. RETC over the years has gained a worthy reputation as being a genuinely open and honest conference, where real issues - including where things didn’t go quite to plan - are discussed. A swift look at the line-up of papers to be presented promises 2017 will be no exception.

Running alongside the Conference is the RETC Exhibition, which has grown to rival any international set-up of its kind. We’ve included a complete layout of the Exhibition floorplan over the page, and a listing of who’s booth is where.

In our experience, everything about the RETC is focused and concise, it is designed for the attendee to get as much out of it as possible. It runs inevitably like clockwork - much to the credit of the organizers - so with a little planning beforehand your three days will be both educational, and equally importantly - enjoyable!
IT ALL STARTED simply enough. In 1991, the New York City Department of Environmental Protection (NYCEP) took a phone call from a utility worker at a power plant along the Hudson River. He indicated that water was shooting up out of the ground in an area where he knew a large water line ran. “At that time, we were treating the water in the Delaware Aqueduct with copper sulfate, which prevents algal growth. We were the only ones doing it, so we sent a team to test the water. The water tested positive for copper sulfate, so we knew it was coming from the Delaware Aqueduct,” explained Adam Bosch, Director of Public Affairs at the NYCEP. Further testing showed that about 75 million liters (20 million gallons) of water per day were leaking into the Hudson River from cracks in the 1940s-era tunnel.

The repair would be anything but simple. At 137km (85mi) long, the Delaware Aqueduct is cited in the Guinness Book of World Records as the world’s longest continuous tunnel. On any given day, it supplies 50-60% of New York City’s drinking water—a metropolis of 8.5 million people. “We could not simply shut down the Delaware Aqueduct. The construction work would require three to four years, and New York City could not survive on the diminished water supply,” explained Bosch.

What would follow would be a more than 25 year effort to bolster New York City’s water supply through augmented water lines and pumping stations, as well as city-wide efforts at conservation and water management to be able to take the Delaware Aqueduct offline for a shortened period of five to eight months.

A key component of the plan is a bypass tunnel that will connect up with structurally sound portions of the aqueduct and run deep below the Hudson for 3.8km (2.4mi). Notably, the tunnel will be bored while the aqueduct is still in service—only after excavation of the bypass will the flow be switched off while testing is done through the bypass tunnel section. At 183m (600ft) below the riverbed of the Hudson, the bypass tunnel in faulted, crumbly limestone will be subject to water inflows at high pressures of up to 20 bar. A specialized 6.8m (21.6ft) diameter Single Shield TBM, manufactured by The Robbins Company for JV contractor Kiewit-Shea Constructors (KSC), will bore the tunnel using components aimed at keeping the crew safe while enabling efficient excavation in the extreme conditions.

Water to the People
The Delaware Aqueduct was completed in 1944—a massive gravity-fed water supply line conceived to aid in the war effort during World War II. The 13.5ft diameter tun-

Desiree Willis of The Robbins Company explains how one TBM will bore through difficult conditions to fix the world’s longest continuous tunnel.
The original Delaware Aqueduct was constructed by drill and blast. Here, the section that will now need repair was blasted in fractured rock with documented inflows of 7.5 to 15 million liters (2 to 4 million gallons) per day.

Muck is removed during construction of the deep launch shaft at Newburgh.
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"We are conducting the repairs now based on increasing demands. The city has grown by 1.5 million people since 1990. Demand for water during that time has actually declined by 38% due to modern appliances such as low flow toilets and water fixtures, but now is the time to act," said Bosch. The agency has effectively decreased demands through several other avenues, including smart metering technology that detects leaks in the distribution system in real time. Water consumption is also broadcast in near real time to all accounts so individuals can see their water consumption and reduce it. They have also challenged local businesses to conserve water—a challenge that has largely been met. “We are more water-efficient now than we have been at any other time. This is one way to make sure there will be enough water without the city’s main artery,” said Bosch.

That main artery is still more than half of the city’s water supply, so the NYCEP had to act in other ways. They are bringing the Croton water supply system back online—a system that has been offline for 15 years—adding 290 mgd. Two pumping stations at Cross River and Croton Falls—reserved for emergency drought conditions—have been retrofitted with new pumps especially for the period when the Delaware Aqueduct will be offline, and will add 240 mgd. Lastly, the Catskill Aqueduct will be rehabilitated, adding a further 40 mgd. The Catskill Aqueduct’s capacity has been reduced by biofilm—a bacterial coating creating friction along the tunnel walls and slowing the flow of water. A massive cleanup involving power washing of the 74 mile long tunnel will boost the flow of water and provide the final boost in supply that New York City will need during the Delaware Aqueduct’s shutdown.

The Bypass Tunnel: Prepping for Excavation

The Delaware Aqueduct Repair requires use of a TBM for safe excavation in the difficult geological conditions. To that end, two massive shafts were constructed—launch shaft 5B in Newburgh, New York, and a retrieval shaft in Wappinger on the other side of the Hudson. The shafts were constructed by drill and blast with concrete lining installed every 100ft. Their construction was completed in March 2016, resulting in an 845ft deep, 30ft diameter shaft at Newburgh and a 645ft deep shaft at Wappinger. The locations were strategic, says Bosch: “At Wappinger, the machine will break through in a residential hamlet so it is not reasonable to start on that side. We didn’t want to disrupt the community there. At Newburgh, the site is fairly large, on a wooded hill across from a cemetery and a closed golf course, so our impact will be minimal.”

The TBM will be launched from a bell-out chamber with a 40ft high ceiling currently under construction. The Newburgh shaft features a complex logistical setup including an elaborate hoisting system designed to service the shaft. The hoisting system will provide a lifting capacity of up to 100 tons to be used during TBM assembly. The same hoisting system can be re-
configured to provide an individual muck hoist to lift out 20 cubic yard muck boxes during the drive, or it can be used as a supply hoist to lower precast segments and linear plant down the access shaft. The tower crane can also be used as a dedicated personnel hoist to operate a 28 person mancage in the shaft, all within the confines of a 30ft diameter shaft.

Once tunneling is underway, the plan will be to line most of the tunnel—about 9,200ft—with steel interliner after the initial TBM excavation. The steel interliner will be much longer than what was initially used on the Delaware Aqueduct, to cover the entire section of poor ground. After segments are placed, the 16ft diameter, 40ft long sections of steel liner will be pulled into place before receiving a final concrete lining.

Unique New York: A Specialized TBM for Difficult Ground

Due to the challenges presented by the Aqueduct Repair, such as difficult geology and considerable water inflows, the TBM had to be designed accordingly. Difficult Ground Solutions (DGS), including powerful drilling, grouting, and water inflow control systems were incorporated into the machine’s design to overcome the expected challenges. “One unique feature of this TBM is the closeable bulkhead, which allows the excavation chamber to be sealed off,” said KSC Tunnel Manager Niels Kofoed. “We expect this to be a key feature in the event that groundwater flows (shunt flows) from the excavated portion of the tunnel cause washout of the annulus grout. Once the bulkhead is closed the groundwater flows are stopped and secondary grouting of the precast liner can be performed, effectively cutting off the flow path of the shunt flows.”

To seal the TBM requires several steps. Knife gates over the muck chute are closed, followed by retraction of the conveyor frame and the belting from the cutting chamber. The bulkhead sealing plate is retracted and finally the stabilizer doors are closed. The sealing system includes emergency inflatable seals as well as the normal lip seals. The inflatable seals are not in running contact with moving parts of the sealing system during boring and can be activated when needed for additional pressure protection of the main bearing of the TBM. The seals are flushed and lubricated with grease to provide better protection when exposed to water with fines.

The TBM includes Difficult Ground Solutions such as enhanced probe drilling. Probe drill trajectories are seen here in red and orange. The TBM was further designed with a 9,500 liter/min (2,500 gallon/min) dewatering capacity using both continuous pumping and emergency pumping during a severe water inflow. The initial dewatering system is designed to transfer fines up to a ¼ inch in size from through the piping and tanks to the tunnel’s dewatering system. The TBM is equipped with two 10 cubic meter dewatering tanks with mixing pumps inside the tanks to prevent fine settlement, thus reducing shutdowns for maintenance and cleaning.

A further measure against high-pressure water inflows involves the use of unique, pressure compensating disc cutters. The 19-inch diameter disc cutters utilize a patented, pressure-compensating retainer to operate cutters at elevated pressures through pressure equalization, and have been lab-tested to 34 bars.

Robbins Project Manager Martino Scialpi further noted that, “The machine is equipped with two drills in the shields for drilling through the head in 16 different positions and a third drill on the erector to drill through the shields in an additional 14 positions. Drilling and pre-excavation grouting will be a routine job to control and minimize water inflows.” To add to that, water-powered, high pressure down-the-hole-hammers will allow for drilling 60 to 100m (200 to 330ft) ahead of the machine at pressures up to 20 bar if necessary.

Coming Up

Robbins worked closely with KSC to ensure that TBM components were designed and sized so all parts were less than 100 US tons and could be lifted with the contractor’s hoist system to fit down the narrow, 270m (885 ft) deep shaft window. A factory acceptance test was held in February 2017. After being shipped to the site, the TBM is to be assembled on a moving cradle at the bottom of the shaft that can then be moved to the tunnel face. Launch is expected in autumn 2017.
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