APRIL 2012

tunnels & tunnelling INTERNATIONAL

Great Britain
Capital time for tunnelling as Crossrail leads major projects list

Hong Kong
Cavern design challenges for West Island Line stations

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Site investigation

Under and over ground ways of reducing risk

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comment

Talking tunnels

In 'his' first appearance for some years *Drifter*, the old *T&T* favourite, returns on page 58 to urge tunnellers to be more talkative. He calls for everyone to become more vocal in his or her support of the industry and in educating others on the importance of underground infrastructure. In a similar vein, the incoming and outgoing chairs of the British Tunnelling Society (BTS) argue the importance of raising tunnelling awareness with politicians and clients. Damian McGirr and Bob Ibell argue that a steady future workload can be achieved by ensuring each city planner has the use of underground space firmly on the agenda. McGirr says the BTS will be central in making this happen.

The All Party Parliamentary Group for Underground Space (APGUS), in which the BTS plays a full part, has done some excellent work in raising awareness in the UK House of Commons, creating several enthusiasts, but perhaps a wider campaign is necessary to reach a frequently sceptical public. And on the world stage the International Tunnelling Association (ITA) continues to make strides in this effort.

London Mayor Boris Johnson brought tunnelling into the national spotlight with the launch of the first Crossrail TBMs (see news page 5). The launch of the machines was carefully timed with the launch of his re-election campaign for Mayor. The industry should be glad, or at least flattered, that he has apparently been converted from bridge to tunnel for a proposed new crossing of the River Thames, and has backed tunnels to improve the route of the now-approved HS2 high-speed rail route through north London to the Midlands and North West.

With the Crossrail project on schedule and a good level of PR from its team, tunnelling is portrayed as the end of jam-packed trains, the saviour of the disgruntled commuter. One can only hope, but should not lose site of the importance of the less glamorous major upgrade of Transport for London's London Underground network to cope with booming passenger levels (see Victoria Station upgrade feature, page 35).

However, the Crossrail photo opportunity was overshadowed in the international press as Swiss investigators said they would be looking at tunnel design as a potential cause of a bus crash that killed 28 people in the Sierre tunnel, including 22 children (see news page 5). The bus is thought to have clipped a kerb in the Swiss tunnel and swerved into a service bay. The bay ended with a head on wall where the bus crashed. Investigators from the Swiss Federal Office for Roads are analysing whether an angled wall at the end of the service bay could have lessened the severity of the crash.

Switzerland, like most countries, knows it could not function without tunnels, but insists on the highest standards of safety and construction. It is no time for the industry to rest on its laurels.

There is no central point for managing the image of the tunnelling industry. It is up to each and every tunneller to meet this challenge and further the profession's reputation. For good reason the general public has frequently kept tunnelling at arms reach with a NIMBY attitude. As tunnelling becomes, safer, quicker, better value for money, and essential for growth, tunnellers need to be vocal in explaining, supporting and when necessary defending the industry and colleagues.

This issue of *T&TI* is packed with successful projects that all stand testament to the industry's ability. When you've finished reading, pass this magazine onto the next person and start spreading the understanding of tunnelling.

Jon Young

On the cover:
A Diamec U6 diamond-bit coring rig; one of a wide range of underground and surface site investigation rigs produced by Atlas Copco

Breakthrough of Double Shield TBM, Ø 12.34m, Clem Jones Tunnel, Brisbane

China, Mixshield, Ø 15.43m

Spain, EPB Shield, Ø 15.20m

Italy, EPB Shield, Ø 15.55m

Australia, Double Shield TBM, Ø 12.34m

WORLD LEADER IN LARGE DIAMETER TBMs.

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Construction companies have successfully excavated more than 440 kilometers of traffic and utility tunnel with diameters of more than 10 meters using Herrenknecht technology. In Shanghai the two world's largest Mixshields (Ø 15.43m) excavated three-lane road tunnels under the Yangtze River. The two giants finished their 7.5km drives one year ahead of schedule and the tunnels were opened to the public in time for the 2010 WorldExpo. Brisbane is reducing above-ground road traffic significantly by investing in efficient underground infrastructure. Two Herrenknecht Double Shield TBMs (Ø 12.43m) tunnelled under the Brisbane River for the Clem Jones Tunnel and two even larger Herrenknecht EPB Shields (Ø12.45m) successfully crossed the finish line at Brisbane's Airport Link. The world's largest tunnel boring machine, the EPB Shield for the Galleria Sparvo road tunnels with a diameter of 15.55m is progressing impressively on the Italian jobsite.

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Tunnel design investigated in Swiss bus crash that killed 28

SWITZERLAND

A coach crashed in a tunnel in Switzerland last month killing 28 people. The vehicle impacted a wall head on, killing both drivers. No other vehicles were involved. Swiss Federal Office for Roads (Astra) was examining if the design of the tunnel was a contributing factor in the crash, according to the Press Association.

The bus is believed to have clipped a kerb as it drove the tunnel, swerved into a service bay and crashed into a head on wall at the end of the bay. Astra was investigating if and angled wall at the end of the bay could have lessened the severity of the crash.

Peter Bishop, chairman of the Road Tunnel Operator Association said, "I've examined the photos carefully. The crash definitely occurred in a lay-by. It was not clear at first as it looked like a built-out structure. The tunnel is 2.5km-long with twin tubes very close together.

"The European Tunnel Register requires tunnels of this length to have lay-bys and safety niches. It seems that the driver lost control of the vehicle and mounted the kerb before hitting the wall."

Swiss prosecutor Olivier Elsig said that there were a few possible causes of the crash.

An autopsy would conclude if the driver was ill, though there was no evidence and that driver error was another possibility.

Bishop said, "The problem with permanently changing the angle of the wall, or introducing crash barriers is the deflection factor. The vehicle will deflect. This can be into the traffic of the tunnel and you can have a far worse accident involving many vehicles.

"It also comes to likelihood, the aperture of this lay-by measured against the entire length of the tunnel is very small. Crash cushions have been proposed in the past, but the angle of impact required is awkward in a tunnel."

Belgian Transport Minister Melchior Wathelet said both drivers were well rested.

They were hired to conduct tourists away from a ski resort and had arrived the night before, resting during the day before departure as per the law. No alcohol was found in the active driver's blood and Elsig said there was no evidence of illness.

Elsig added that the bus was new, and that initial investigations suggested the coach was not exceeding the 100kph speed limit.

Swiss journalist Ruth Seeholzer said that driving conditions were normal and the two-lane tunnel was not busy with traffic when the accident happened.

Investigations were ongoing as T&TI went to press. Bishop said, "Speed is the vital factor in tunnel crashes. It would have made an awful difference in this case as the smallest error of judgement is needed for a disaster.

"I don't think a catastrophe of this magnitude could have been prevented, but we are pushing for speed reductions with the Highways Agency.

"All tunnel designers will now be looking at their structures. There is a forum in April near Farnborough, UK that did not have this accident on the agenda, but I think now it will be a serious topic."

Rome's B1 Line metro completes

ITALY

Excavation of the third extension to the B1 metro line in Rome, Italy finished last month. A Seli EPBM was used by the firm's contracting side, which was appointed as the tunnelling subcontractor. Main contractor was a JV of ATI Salini Costruttori and Tecnimont. Roma Metropolitane was the developer.

The 522m drive from Conca d'Oro to Piazzale Jonio, both in the city's northeast, began in June 2010. The complete tunnel is 1.1km-long and 10m in diameter. Previous portions were completed at the end of 2009, for the Conca d'Oro to Gondar portion and September 2010 for the Conca d'Oro to Piazzale Bologna section.

Geology encountered was clay

Crossrail TBM launch amid calls for Crossrail Two

GREAT BRITAIN

London mayor Boris Johnson and Secretary of State for Transport Justine Greening on 13 March pushed the button to fire up the first Crossrail TBM. Johnson hailed the 'Neo-Victorian' level of investment that has flowed from the Olympics and tube upgrades.

He added, "These mighty tunnelling machines […] these voracious predators of the Pleistocene clay of London will set forth on a journey that tens of millions of Londoners will follow on the trains that will hopefully be built by a British company… providing all necessary competitive guidelines are followed in the tender process of course.

"The sight today of these tunnelling machines primed for action is a significant step forward in the construction of this vital infrastructure project to add ten per cent to the London Underground capacity... and while I have Madam Transport Secretary Greening here, can we trust that Crossrail Two will soon follow this first endeavour?"

Greening made no reply.

The two 7.1m Herrenknecht EPBMs were named Ada after the computer programming language and Byron's daughter; and Phyllis after Phyllis Pearsall who created the London A-Z street atlas. The Crossrail western tunnels will be excavated by the BAM Ferrovial Kier (BFK) JV.

See feature, page 26 for more.

Right: Johnson and Greening push the button together to 'start' the TBMs

Cleaner Seas pipe jack machine recovered

GREAT BRITAIN

Tunnel works were concluded last month on the Cleaner Seas for Sussex project near Brighton, UK.

The TBM that linked the sewerage works with the long sea outfall at Friars Bay near Brighton, UK (see feature, *T&TI* April 2011, page 33) has been lifted from its submarine reception pit. The 1.8m i.d., 1km drive was executed by an Iseki pipe jacking TBM.

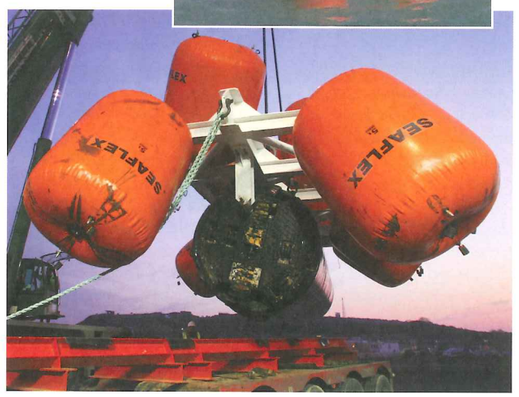
The main contractor, the 4Delivery JV was comprised of Costain, United Utilities and MWH. The tunnelling subcontractor that executed the Friars Bay works was UK-based Joseph Gallagher.

The ambitious drive had to descend sharply to a second shaft at the base of the cliffs before continuing out to the outfall pipe that was laid in a trench. A submarine reception pit of approximate dimensions 13.5m x 8m x 8m was filled with a sea-dredged granular ballast gathered from a site near the Isle of Wight.

Prior to recovery, the machine's watertight doors were shut and a positive internal air pressure applied. The cleared tunnel was flooded, floatation tanks were attached and the machine rose, ready to be recovered.

Jim MacIntyre, project manager for client Southern Water said, "Late July 2010 marked the start of the tunnelling and [the Friars Bay TBM] recovery marks the end. This is a momentous milestone for the project and takes us one step closer to completing the project and bringing cleaner seas to Sussex."

The Cleaner Seas project cost around GBP 300M.



Right: The marine extraction operation was successful

Arup wins HS2 environmental overview services…

GREAT BRITAIN

Arup last month won a contract for provision of environmental overview services for the UK's HS2 rail link. Supported in its role by URS Scott Wilson, the GBP 7M (USD 11.1M) award was the first 'Lot Three Environmental Services' contract awarded by the client.

Arup will coordinate and provide 'technical leadership' to the winners of the remaining four packages to produce an overall environmental statement from their impact assessments.

The four remaining impact assessment packages to be awarded under lot three will cover: natural environment, i.e. biodiversity, water, geology and visual impact; historic environment, i.e. built heritage and archaeology; built environment, i.e. townscape, traffic an transport, waste and planning policy; and finally community, i.e. noise, air quality, community, property and agriculture. The contract began on 13 February and will last until the end of 2013.

Arup global rail leader Colin Stewart said, "Arup has been working with HS2 since May 2009, conducting the initial route engineering studies. We are very pleased to be helping implement the next stage of this project."

… and prepares to design new Euston

GREAT BRITAIN

Arup will also produce preliminary designs to transform Euston Station, London, UK, into the terminus for the impending HS2 rail link to Birmingham. A new underground ticket office will be required in addition to other facilities to accommodate the new services from the station.

The award was worth GBP 10M (USD 15.68M). Work will run until the end of 2013.

Alison Munro, HS2 chief executive said, "Our long term vision for Euston Station is to provide the principal rail gateway for high speed rail services from London to the West Midlands, and onto the north-west and north-east of England and Scotland.

"Following a comprehensive selection process, we have awarded this contract to Arup, supported by Grimshaw and Costain, for innovative approaches towards engineering, architectural design and construction logistics."

News in brief

Crossrail awards Victoria Dock portal contract to Vinci
Contract 340 was awarded to Vinci Construction UK. Andy Mitchell, Crossrail programme director said, "Crossrail has awarded the last portal contract. The Royal Oak Portal completed last year. Construction of the portals at Pudding Mill Lane and Plumstead are underway. Construction of the North Woolwich portal will begin in May 2012 and Victoria Dock in autumn 2012."

Tunnel System Number Three complete for Sochi
The road tunnel drive for 'Tunnel System Number Three' on the combined rail and motorway link to the 'Adler and Alpica Service Mountain Health Resort' 2014 Russian Winter Olympics site has been completed. Contractor SK Most also built a 5,800m-long gallery.

Doubts over tunnel expansion to solve Perth traffic increase

AUSTRALIA

Lobby group City Gatekeepers said extra lanes in the Northbridge road tunnel in Perth, Australia would not ease congestion caused by government development plans.

The Western Australia State Government announced the AUD 57M (USD 60.68M) tunnel project last month. It would add one lane in each direction to take on the extra traffic caused by closure of a road for a waterfront development project. The project will be completed by May 2013 before the development gets underway.

Group convenor and spokesman Linley Lutton said, "If the government's gutsy enough and really understands what it's doing, then they should actually cut Riverside Drive now.

"It should be the first thing they do because what they're saying is there's not going to be a major traffic impact by this or it can be dealt with, but we know that's not the case. If they are so committed to this, let people experience it but they know that there's going to be a major problem."

ITA-AITES Indian seminar

INDIA

During March a workshop on tunnelling for hydroelectric projects was held in Delhi and in Kashmir, India. The workshop, which was held under the banner of the ITAtech and organised by Halcrow and HCC (Hindustani Construction Company) was aimed at knowledge sharing between those associated with tunnelling, particularly related to hydro tunnels, on latest appropriate technology, safety and risk management approaches. The workshop was held over four days. The first day of the workshop was held in Delhi and was attended by representatives of the National Hydro Power Corporation (NHPC) and Tehri Hydroelectric Development Corporation THDC). The final three days were held on the project site of the Kishanganga Hydroelectric Project, near Srinagar in Kashmir, Northern India. Presentations and workshop discussions were led by Remo Grandori of Seli, Lok Home of Robbins, Gunnar Nord and Anders Ostberg of Atlas Copco and Odd-Bjorn Kleven of Normet, and Martin Knights and Mike Palmer of Halcrow. The Kishanganga Hydroelectric Project is under construction by the JV of HCC and Halcrow. The mountainous terrain limits construction access to the headrace tunnel. Drill and blast construction techniques are being employed for construction of approximately 8km of the tunnel, working from an adit near the upstream end. The remaining 15.5km of the tunnel is being constructed using a double-shield TBM operated by Seli and erecting a concrete segmental lining.

Gopal Dhawan, director of NHPC, recently stated that only 25 per cent of Indian hydropower has been tapped. On the eve of the workshop an announcement was made in the Indian press that the Delhi Metro Rail Corporation (DMRC) had announced it's plan to operate the highest number of TBMs simultaneously in any urban centre across the world to ensure that construction on the city's busiest stretches do not cause major traffic congestion, with as many as 35 TBMs.

The workshop provided excellent opportunities for clients, contractors and equipment suppliers to discuss openly the challenges and solutions that are encountered on tunnelling projects in the Himalayas.

ITA held its World Tunnellling Congress in Agra in 2008 and President Martin Knights promised to the Indian Minister of Hydropower and Water that ITA would support training and seminars aimed at sharing best practice for India's infrastructure programme. The recent ITAtech seminar initiated by Halcrow and supported by Robbins, Seli, Normet and Atlas Copco is part of that commitment.

Right: The ITA delivered the promised workshop

News in brief

Australian national code of practice raises concerns
Changes to the Queensland code of tunnelling practice will be adopted by the entire country. An Australasian Tunnelling Society spokesman said, "In the opinion of the ATS, there are a number of inclusions in the revised code which are potentially onerous and/or ambiguous." A full list of changes can be viewed at: www.deir.qld.gov.au/workplace/resources/pdfs/tunnelling-cop-errata.pdf

New independent Crossrail complaints commissioner
Stephen Jolly has been appointed as the new commissioner. Jolly will act as an independent mediator in unresolved disputes between Crossrail and the public. The appointment was effective as of 19 March.

Tunnel light reorganisation
As a result of a reorganisation of the F W Thorpe group into a number of companies dealing with niche markets, the tunnel lighting activities of Thorlux have been transferred to an independent company within the Thorpe group called TRT Lighting, standing for Thorpe Road & Tunnel Lighting. TRT is now setting up a new factory in Redditch, England, about 7.5 km from the existing works. The company will work with P Ducker Systems in co-operating in the incorporation of lighting within complete tunnel control systems.

German minister and ambassador visit Panama
German foreign minister Guido Westerwelle visited Panama City's first metro construction site. The first of two 9.7m-diameter Herrenknecht machines set to excavate the 6.4km of tunnels was launched in January.

Crossrail Liverpool Street award and archaeology

GREAT BRITAIN

Laing O'Rourke has been chosen to construct the Liverpool Street Crossrail station. The value of C502 is approximately GBP 300M.

The Mott MacDonald designed station will be built below Liverpool Street Station, Moorgate Station and Finsbury Circus. Laing O'Rourke will construct two ticket halls, Broadgate in the east and Moorgate in the west. The existing Moorgate hall will be expanded for this purpose. Construction will commence later this year.

Broadgate posed an archaeological problem and a Crossrail spokesman said, "The site of the Broadgate ticket hall sits directly above a 16th Century burial ground belonging to the Bethlehem Royal Hospital. Investigations by Crossrail archaeologists have confirmed the presence of up to 4,000 complete human skeletons two to 4m below street level. Below this level there is the possibility of Roman finds as it is just outside the wall of Roman Londinium.

"Excavation of the human remains will be completed before construction of the new Broadgate Ticket Hall commences. This will enable archaeologists to record and preserve London heritage and history. Crossrail will carefully rebury the remains after consulting with the Ministry of Justice."

The spokesman added, "The burial site has been detailed on maps since the 16th century so it wasn't a new find. It was first uncovered in modern times by the Broadgate Centre in around 1985. In early 2011 a Crossrail trial pit was dug and later in 2012 the full investigation will be undertaken by our in house team and Museum of London Archaeology.

The new Liverpool Street Station will provide interchanges with London Underground's Northern, Central, Metropolitan, Circle and Hammersmith & City lines, connections to Stansted airport and National Rail services at both Liverpool Street and Moorgate stations.

Andy Mitchell, Crossrail programme director said, "As with the Paddington, Farringdon and Whitechapel contracts, high quality bids were received for Liverpool Street station. The main construction contract for Tottenham Court Road station will be the next to be awarded in mid-2012."

New boss for Aker Wirth

GERMANY

Aker Solutions' German subsidiary Aker Wirth appointed a new manager on 1 March. Einar Bronlund took over from Christoph Kleuters who requested to leave.

Thor Arne Haverstad, executive vice president and head of drilling technologies for Aker Solutions said, "Bronlund has the right experience, qualifications and personality to manage our operations in Erkelenz. I look forward to working closely with Bronlund and his team, and to continue to develop our operations and products."

On Kleuters, Haverstand added, "In 1999 Christoph Kleuters was instrumental in saving the company from insolvency and laid the foundation for what Aker Wirth is today – a successful operation with a promising future. We are very thankful for Christoph's efforts and wish him great success."

An Aker Wirth spokesman said, "Bronlund was born in 1960 in Trondheim, Norway, where he studied Marine Engineering at the Norwegian Institute of Technology. He completed an MBA in the mid-1980s at IESE Business School in Barcelona, Spain. and was a management consultant at A.T. Kearney in Dusseldorf, Germany in the 1990s. Since 2006 he has worked in various management positions at Aker Solutions , most recently as CFO of Aker Wirth."

Einar Bronlund replaced Cristoph Kleuters last month

News in brief

Lemminkainen-YIT nuclear power cooperation
Lemminkainen Group and YIT Corporation have signed a letter of intent on cooperation in nuclear power plant construction projects to be implemented in Finland. Negotiations with plant suppliers are ongoing. "We are providing a strong Finnish alternative," said YIT Corporation president and CEO Juhani Pitkakoski.

Delhi Metro film award
A film on the engineering challenges faced by the Delhi Metro in India during its second phase of construction has won the National Award in the 'Best Promotional Film – Non-Feature films' category. It was called: 'The Dream Fulfilled – Memories of the Engineering Challenges'. It was a 30 minute documentary highlighting technical difficulties. The awards were the 59th such ceremony.

Cairo Line Three open
Line Three part one of the Cairo metro was opened on 21 February. This first phase includes five underground stations (Attaba, Bab el Shaaria, El Geish, Abdou Pasha and Abbasia) and serves the eastern part of Cairo from the city centre. Once completed, Line Three will cross the Egyptian capital from east to west. It was built by Vinci, Bouygues, Orascom and Arab Contractors JV.

First Airport Link 'drive'
Queensland Premier Anna Bligh became the first person to officially drive the Airport Link tunnel at the end of February - underground from Bowen Hills to Toombul. Australia's largest and most complex road infrastructure project was over 95 per cent complete with just five months of construction left.

Growth from Atlas Copco, but caution

SWEDEN

Atlas Copco has reported continued growth in orders and revenues during Q4 with record sales and operating profit in provisional figures for the full year of 2011.

President and CEO Ronnie Leten said, "We had a solid year that was fantastic for Atlas Copco. Demand for our products and services was better than expected during the quarter."

Revenues increased organically by 16 per cent to SEK 22.3bn (USD 3.38bn) in the fourth quarter and the operating profit was SEK 4.6bn (USD 0.7bn) corresponding to a slightly lower margin of 21.6 per cent.

For the full year, the margin increased on 2010 from 19.9 per cent to 21.6 per cent. But demand is expected to weaken from the current high level.

"We have a good starting point but a challenging task ahead," said Leten, "the global outlook is difficult to predict and we will continue seeking long- and short-term growth opportunities."

Features of 2011 activity reported include development of manufacturing capacity in Asia, acquisitions and investment in competence in all markets.

Demand for rock excavation equipment, chiefly due to mining, remained high and increased in most areas, although they decreased in Africa and the Middle East from the high levels of 2010. There were records sales in South America and Australia, with a stabilisation and slight increase in Europe. There were also increases in all major mining and construction markets in Asia. This is Atlas Copco's largest regional market for rock excavation at 27 per cent, followed by North America at 23 per cent and Europe at 21 per cent.

During 2011 it acquired 11.3 per cent of minority shares in Atlas Copco India and delisted the company from Indian exchanges.

Yongnam's sixth year of record earnings

SINGAPORE

Singapore-based Yongnam Holdings announced a sixth consecutive year of record earnings. The company attributed this to stronger a contribution from higher margin 'specialist' civil engineering projects. This division of Yongnam has executed cut and cover projects, notably Singapore Circle Line stations.

In a statement on Wednesday the company revealed a 16.5 per cent jump in net profit to SGD 63.4M (USD 50.7M). This was despite a 0.7 per cent drop in revenue to SGD 332.7M (USD 266M).

A spokesman said, "Geographically, Singapore continued to be the group's core contributor, accounting for SGD 284.7M (USD 227.6M) or 85.6 per cent of group revenue, down six per cent from SGD 302.6M (USD 241.9M) in the 2010 financial year.

"Revenue booked from the rest of Asia (excluding Singapore) grew from SGD 24.5M (USD 19.6M) in 2010 to SGD 44.3M (USD 35.4M) in 2011, accounting for 13.3 per cent whilst the Middle East contributed the balance SGD 3.7M (USD 2.96M) or 1.1 per cent of total revenue."

Seow Soon Yong, Yongnam CEO added, "Our consistent performance shows a strong competitive advantage in the infrastructural and specialist construction industry."

Strabag betters output forecast

AUSTRIA

Strabag exceeded its expected output forecast for 2011 by EUR 0.3bn (USD 396M). The total EUR 14.3bn (USD 18.9bn) output figure was up from EUR 12.8bn the previous year.

The order book stood at EUR 13.4bn (USD 17.7bn), down nine per cent on the level at the end of 2010. A Strabag spokesman said that the company should see output in 2012 roughly equalling that in 2011.

The spokesman added, "Even if uncertainties regarding the actual economic environment – economic growth in the individual markets, the height of public spending, and the financing environment for our clients – make planning difficult, Strabag [will see] relatively stable results for the 2012 financial year.

Townsend joins Parsons tunnel operation

USA

Bradford Townsend has joined Parsons' bridge and tunnel division. He will take responsibility for technical direction and project delivery.

A spokesman said, "Prior to joining Parsons, Townsend served as west region deputy practice manager for tunnels – senior associate for an engineering firm in California. In that role, he oversaw and directed corporate practice for tunnel projects and provided technical support.

"His experience includes work as deputy chief engineer of the USD 20bn Taiwan high-speed rail project as well as leadership roles on the Hai Van Pass Tunnel in Vietnam."

Parsons president Tom Barron added, "His technical acumen, and management skills present us with a unique asset."

News in brief

Joos joins Aecom heads
David Joos has joined the Aecom board of directors. Joos recently served as chairman of the Board of CMS Energy Corporation, a New York Stock Exchange-listed public electric and natural gas utility. Previously, he served from 2004 to 2010 as president and chief executive officer of CMS Energy and as chief executive officer of its principal subsidiary, Consumers Energy Company.

Caterpillar Japan buys Caterpillar Tohoku
Caterpillar announced that Caterpillar Japan had acquired Caterpillar Tohoku effective 1 March. With the acquisition, Caterpillar Japan restructures its distribution network in Japan. For more than 40 years, Cat Tohoku was independently owned and operated.

Morgan re-appointed chairman of Crossrail
Crossrail Limited announced that Terry Morgan CBE has been re-appointed by the Crossrail board as non-executive chairman for a three-year term from 31 May 2012. Morgan was appointed chairman of Crossrail in June 2009. He was previously chief executive of Tube Lines.

Bekaert director reappointments
The Board of Directors of Bekaert has decided to extend the retirement age for Directors from 67 to 69 years. The Board also decided to propose Baron Buysse, Baron Bekaert, Bert De Graeve, Count Charles de Liedekerke, Anthony Galsworthy, and Hubert Jacobs van Merlen, Maxime Jadot and Manfred Wennemer for reappointment by the Annual General Meeting of Shareholders on 9 May 2012.

Tsuen Wan Drainage Tunnel breakthrough

Left: Breakthrough on the USD 142M drainage tunnel

Hong Kong's USD 142M Tsuen Wan Drainage Tunnel broke through on 27 February. A spokesman for TBM manufacturer and JV partner Seli said the TBM and other facilities were already being dismantled as *T&TI* went to press.

The project was commissioned by the Hong Kong Drainage Services Department following a severe flood in June 1997. It began in December 2007 and will be fully completed in 2013.

Mott MacDonald was brought in to produce a 'drainage master plan' for the district in 1998. The approximately HKD 1.1bn (USD 142M) will supplement existing drainage built in the 1960s and 1970s.

Excavation of the 5.1km-long, 6.5m id tunnel began in March 2010 by a contracting JV of Maeda, CRGL and Seli. Geology was extremely strong and abrasive fresh rocks that included crystal ash tuffs of the volcanic group, Tai Po Granodiorite and a variety of crosscutting dykes that included basalt, rhyolite, fine-grained granite and quartz. Rock strength reached 410MPa. Sections of the excavation were 200m below the surface.

Seli listed abrasive ground and a narrow work space as the two main challenges on the project. Steeply sloped terrain was also a consideration and the tunnel portal was 14m above the road level and located between residential areas, which resulted in logistic and working time restrictions.

The 7.72m-diameter double shield, hard rock TBM was equipped with probe drills to investigate rock and water ahead of the tunnel face. The cutterhead was equipped with 47 cutters with a 19-inch diameter and powered by eight 315kW motors. Breakout torque was 6,600kNm.

The tunnel was designed to cope with a one in 200 years rainstorm, a capacity of 210 cubic metres of water per second. An outfall will discharge the water into the sea at Yau Kom Tau on the north coast of Tsing Yi Island.

Sidney Lui, Mott MacDonald project manager for the tunnel said, "Dense urbanisation has made it difficult to meet flood protection standards by upgrading existing surface drainage […] the early design phase focused on optimising the location of the intakes and the tunnel alignment. We needed to intercept as much run-off as possible during an extreme rainstorm but for ecological reasons had to keep water flowing in the streams during normal conditions. As a result, the tunnel's designed to intercept water only when rainfall exceeds 30mm per hour."

Reinforced concrete spiral ramp structures were built within the 20m-diameter, 10 to 20m-deep intake shafts. Lui added, "The slope on the spirals is gentle so the water runs down into the tunnel in a smooth, controlled stream. That prevents pockets of air from being forced into the tunnel, which could cause water to back up and to overtop the approach channels."

The client refused to allow interested parties on the project to give detailed comment on the completion in hindsight.

Breakthrough at Tsuen Wan marked the end of tunnelling works for a trio of large drainage projects to break through in Hong Kong in the space of a year. The others were the Lai Chi Kok Drainage Tunnel which broke through in December (see News In Depth, *T&TI* February 2012, page 14), and the Hong Kong West Drainage Tunnel which broke through in February 2011 (see 'Ceremony for longest Hong Kong drain', tunnelsandtunnelling.com).

Alex Conacher

TBMs in squeezing ground conditions

In Part I of their contribution (see *T&TI* March pages 16-20), Marco Ramoni of Basler & Hofmann and Georgios Anagnostou of ETH Zurich described the specific problems of and discussed possible countermeasures for dealing with squeezing ground during TBM tunnelling. Part II introduces practical design aids for the planning engineer that allow for a quick and easy evaluation of the feasibility of TBM drives in squeezing ground

Left: The 1.5km deep Olmas Trans-Andean tunnel is being cut through sever squeezing ground

TBM tunnelling in squeezing ground represents a real challenge for all of the parties involved. It is well known from tunnelling experience that even small convergences of 100–200mm, which would not be problematic in conventional tunnelling, may lead to major problems both in the machine and in the back-up area (Ramoni and Anagnostou, 2010b).

In the planning phase, a careful evaluation of the expected tunnelling conditions is essential. For squeezing ground, the specific potential hazards that have to be evaluated include sticking of the cutter head, jamming of the shield, jamming of the back-up equipment, inadmissible convergences of the bored profile and damage to the tunnel support. In early project phases this assessment has to occur quickly and be cost-efficient. On the one hand, the general feasibility of a TBM drive in squeezing ground has to be proven. On the other hand, the tunnel sections requiring detailed investigations in later project phases have to be identified.

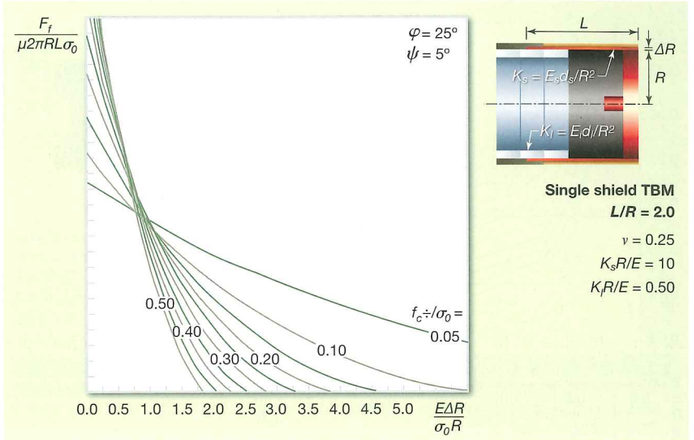
The authors have worked out decision aids for the planning engineer in respect of the two specific problems of jamming of the shield and damage to the tunnel support in shielded TBM tunnelling (Ramoni and Anagnostou, 2010a; Ramoni et al., 2011). These are design charts which allow for a quick and easy assessment of the thrust force required for overcoming shield skin friction (for gripper TBMs as well as for both single and double shielded TBMs) and the segmental lining loading (for both single and double shielded TBMs).

Computational model

Working out the design charts required the execution of about 20,000 calculations. Managing such a high computational effort was possible through the development of a computational method and model specifically for this purpose.

The computations have been executed applying the so called steady state method (Anagnostou, 2007; Nguyen Minh and Corbetta, 1991) – a numerical procedure implemented in the finite element code HYDMEC of the ETH Zurich which solves the advancing tunnel heading problem in just one single computational step, thus enabling major computational time saves.

The computational model was kept deliberately simple, taking into account axial symmetry and the Mohr-Coulomb yield criterion. However, in spite of its simplicity, the computational model properly simulates all of the major system components, i.e. the shield and tunnel support with all of their main characteristics (e.g. the radial gap size between shield and ground, and the type and location of the backfilling of segmental linings), thus providing the maximum number of generally valid and valuable results with the minimum number of assumptions. For a more detailed description of the computational model, the readers are referred to Ramoni and Anagnostou (2010a, 2011b, 2011c) and Ramoni et al. (2011).



Right: Figure 1, nomogram for determining the thrust force Ff required for overcoming the shield skin friction of a single shielded TBM (after Ramoni and Anagnostou, 2010a)

Nomograms for assessing the required thrust force

Concerning the risk of shield jamming, it is essential to have information on frictional force when designing a new TBM and when assessing the feasibility of a proposed TBM drive. Concerning the utilisation of a second-hand TBM, checks have to be made as to whether the installed thrust force is sufficiently high or whether the TBM has to be refurbished.

The thrust force Ff required for overcoming shield skin friction generally depends on all of the parameters of the problem under consideration: the material constants of the ground (Young's modulus E, Poisson's ratio ν, uniaxial compressive strength fc, angle of internal friction φ and dilatancy angle ψ), the initial stress σ0, the characteristics of the TBM (tunnel radius R, radial gap size ΔR, shield length L and shield stiffness Ks), the skin friction coefficient μ and the stiffness of the lining Kl. The dimensionless nomograms are based on the numerical results of a comprehensive parametric study covering the relevant range of material constants, in situ stress and TBM characteristics. As the number of variables is still large, a trade-off has had to be made between the completeness of the parametric study and the cost of computation and data processing. For more details, as well as for a discussion of the underlying assumptions, the reader is referred to Ramoni and Anagnostou (2010a).

Each nomogram applies to a different TBM type (gripper TBM, single shielded TBM or double shielded TBM) and normalised shield length L/R as well as to a different value of the angle of internal friction φ.

Each design chart includes a band of curves (each curve corresponding to another value of the normalised uniaxial compressive strength fc/σ0) showing the normalized required thrust force Ff /(μ2πRLσ0) as a function of the dimensionless product of E/σ0 by ΔR/R. As an example, one of a total of 45 dimensionless nomograms (Ramoni and Anagnostou, 2010a), which applies for a single shielded TBM, is depicted in Figure 1 (above and right).

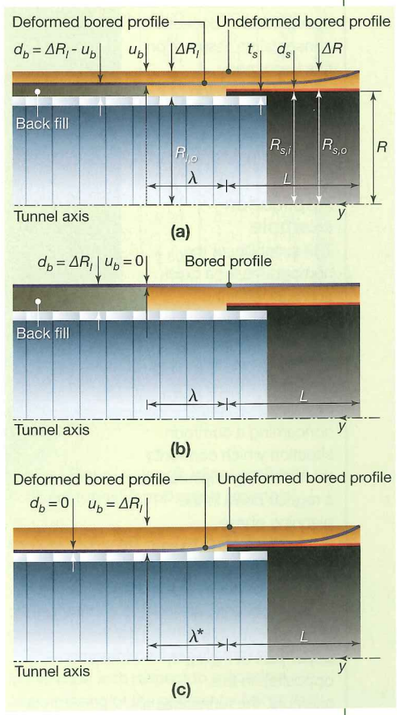
Nomograms for assessing the segmental lining load

As regards the risk of lining overstressing, an estimation of the segmental lining load is essential to any assessment of a shielded TBM drive in squeezing ground. A realistic estimate is possible only if due account is taken of the type, location and thickness of the backfilling.

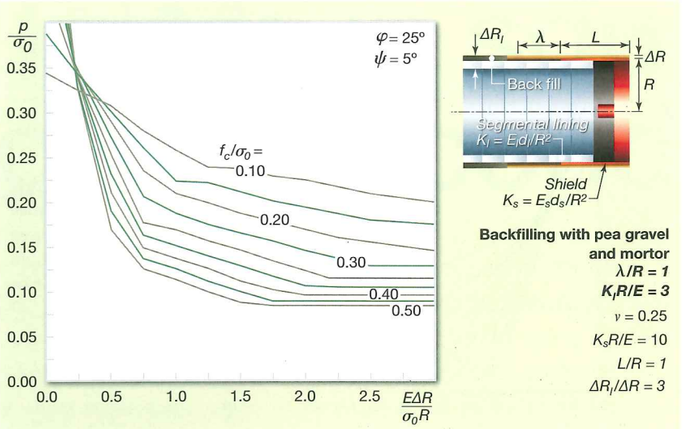
This is a challenging problem, because the thickness of the backfilling is not known a priori but depends on the intensity of the squeezing, i.e. on the deformations of the bored profile between the tunnel face and the point where the backfill is installed (see Figure 2, right).

Analogously to the thrust force Ff required for overcoming shield skin friction (see above), the ground pressure p acting upon the segmental lining depends on the material constants of the ground (E, ν, fc, φ and ψ), on the initial stress (σ0), on the characteristics of the TBM (R, ΔR, L and Ks) and, additionally, on the characteristics of the backfilled segmental lining (stiffness Kl, radial gap size ΔRl and location of backfilling λ).

Figure 3 (page 16) shows, by way of example, one of a total of 45 dimensionless nomograms (Ramoni et al., 2011) applying to a segmental lining that is completely backfilled with pea gravel and mortar at a distance of half a boring diameter behind the shield. Each nomogram applies to a different pair of values (λ/R, KlR/E) describing the location where the backfilling occurs and the stiffness of the segmental lining, respectively. The diagrams of each figure apply to different values of the angle of internal friction φ and show the normalised ground pressure p/σ0 as a function of the dimensionless parameter



Right: Figure 2, thickness of the backfilling db depending on the deformations of the bored profile ub: (a) general case; (b) borderline case of practically zero ground deformations between the face and the location of the backfilling; (c) rapidly converging ground closing the gap around the lining before completion of backfilling (Ramoni et al., 2011)



Backfilling with pea gravel and mortar
λ/R = 1
KlR/E = 3
ν = 0.25
KsR/E = 10
L/R = 1
ΔRl/ΔR = 3

Above: **Figure 3, nomogram for determining the segmental lining load p (after Ramoni et al., 2011)**

(E/σ0)(ΔR/R) and of the normalised uniaxial compressive strength fc/σ0. Other parameters (ν, KsR/E, L/R and ΔRl./ΔR) have been kept constant, either because their influence on the normalised ground pressure p/σ0 can be disregarded or because a conservative assumption has been made. A detailed discussion of the underlying assumptions can be found in Ramoni et al. (2011).

Application example

The suitability of the nomograms for a quick and cost-effective preliminary assessment of a TBM drive in squeezing ground will be shown by means of an application example concerning a common situation which confronts the tunnelling engineer on a regular basis in the planning phase.

The example is based on the longitudinal profile of a tunnel with a known geology (as shown schematically in the upper part of Figure 4, opposite). In this example, the tunnel has a diameter of 10m and crosses four different rock mass types (denoted by A–D) at different depths (350–550m). At issue is the identification of the critical stretches with respect to a possible jamming of the shield or to overstressing of the segmental lining under the assumption that the tunnel will be driven with a single shielded TBM.

Below: **The McNally lining on the Olmas tunnel crossing the Andes is designed to flex and move as the ground squeezes**

The table in the bottom part of Figure 4 (opposite) shows the preliminary assessment based upon the nomograms of Ramoni and Anagnostou (2010a) and Ramoni et al. (2011).

The hazard scenario 'jamming of the shield' can be assessed by comparing the required thrust force Fr with the installed thrust force Fi which is planned for the TBM. For the sake of simplicity, Figure 4 contains only the results for the operational state 'restart after a standstill' (the conditions during the boring process are not considered here). Please note that for this state Fr = Ff applies, i.e. the required thrust force Fr is equal to the thrust force required for overcoming shield skin friction Ff, as the boring thrust force is not taken into account when analysing this state (Ramoni and Anagnostou, 2010a).

The first step in the computation of the required thrust force Fr consists in the choice of the nomogram to be used. For example, for the tunnel section B (Figure 4) – considering the present boring diameter

D of 10m (i.e. a boring radius R of 5m) and the shield length L of 10m (resulting in a ratio L/R = 2) as well as the angle of internal friction φ of 25° – the nomogram of Figure 1 applies. Taking into account the actual uniaxial compressive strength (fc = 3MPa) and the initial stress (σ0 = 10MPa), the appropriate curve of Figure 1 is chosen according to the ratio fc/σ0 = 0.3. In the next step, the dimensionless factor (EΔR)/(σ0R) = 1 is computed according to the actual values of the Young's modulus E (1000MPa), the radial overcut of the shield ΔR (50mm), the initial stress σ0 (10MPa) and the boring radius R (5m). This dimensionless factor is then entered into the nomogram in order to depict the value of the normalized required thrust force for overcoming shield skin friction Ff /(μ2πRLσ0), which is 0.26 in this example. Finally, a simple conversion (and bearing in mind that Fr = Ff applies in this case) allows the required thrust force to be determined. In this example Fr = 368MN, which clearly exceeds the assumed installed thrust force Fi of 150MN.

Assessment

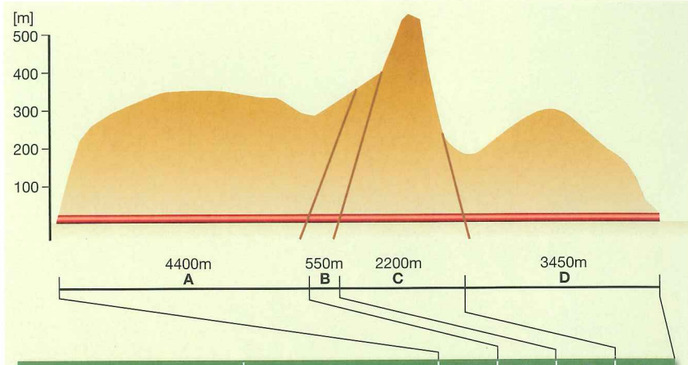
The computational results indicate that the tunnel section B (Figure 4) is critical with respect to the risk of shield jamming. Assessing the feasibility of the TBM drive, the planning engineer should also be able to check which countermeasures would lead to a reduction of this risk. Such a preliminary assessment is possible by applying the nomograms. For example, repeating the same computation as above with ΔR = 10cm (overboring) instead 50mm (normal overcut) indicates that doubling the radial gap size ΔR leads to a decrease of the required thrust force Fr from 368MN to 110MN. According to this, for the example in question, the conclusion can be drawn that overboring (if it can be applied with sufficient reliability) would reduce the risk of shield jamming significantly.

The assessment of the hazard scenario 'overstressing of the segmental lining' can be carried out analogously by comparing the ground pressure p (load) with the bearing capacity of the lining pmax.

In this case, the appropriate nomogram is selected on the basis of the distance λ between the shieldtail and the location where the backfilling of the segmental lining is completed, the stiffness Kl of the segmental lining and the angle of internal friction φ. For example, for the tunnel section B (Figure 4) λ/R = 1, KlR/E = 1.8 (the segmental lining is assumed to be 300mm thick) and φ = 25° apply. As the nomograms of Ramoni et al. (2011) have been worked out for selected values of the ratio KlR/E (i.e. one, three and 10), the computation in this case requires a linear interpolation between different nomograms (which, for the sake of economy, is not reported here).

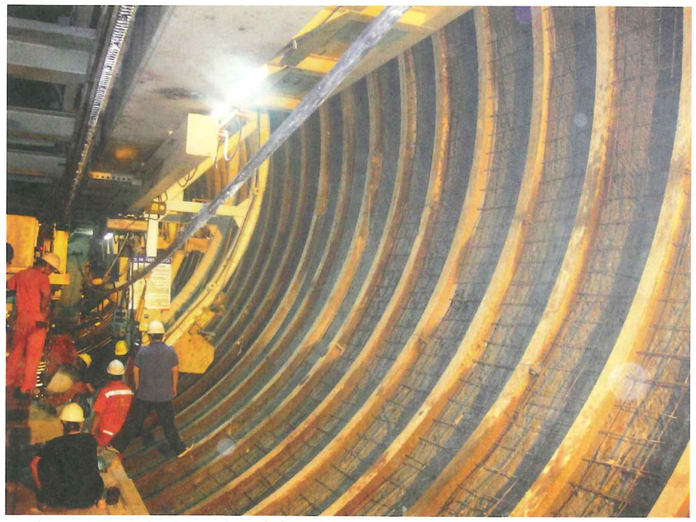
The output of the nomograms is the ratio between the ground pressure p acting upon the segmental lining and the initial stress σ0. For the example of tunnel section B, p/σ0 = 0.14 (calculated according to the main inputs fc/σ0 = 0.3 and (EΔR)/(σ0R) = 1 as above) and therefore the result is p = 1.4, which exceeds the assumed bearing capacity of the segmental lining, which is pmax = 1.2MPa.

The computational results indicate again, in this case with respect to a possible overstressing of the segmental lining, that



		A	B	C	D
Ground					
Young's modulas	E [MPa]	2000	1000	3000	2500
Poisson's ratio	ν [-]	0.25	0.25	0.25	0.25
Uniaxial compressive strength	f_c [MPa]	2.5	3.0	3.5	3.9
Angle of internal friction	φ [°]	30	25	35	30
Dilatancy angle	ψ [°]	10	5	15	10
Unit weight	γ [kN/m³]	25	25	25	25
Initial stress					
Depth of cover	H [m]	350	400	550	300
Initial stress	$\sigma_0 = H^{\gamma}$ [MPa]	8.75	10.00	13.75	7.50
TBM					
Boring diameter	D [MPa]	10	10	10	10
Boring radius	R [m]	5	5	5	5
Radial gape size (shield)	ΔR [cm]	5	5	5	5
Length (shield)	L [m]	10	10	10	10
Skin friction coefficient	μ [-]	0.45	0.45	0.45	0.45
Backfilled segmental lining					
Young's modulas	E_l [MPa]	30000	30000	30000	30000
Thickness	d_l [cm]	30	30	30	30
Stiffness	$Kl = E_l d_l / R^2$ [MPa/m]	360	360	360	360
Uniaxial compressive strength	$f_{c,l}$ [MPa]	20	20	20	20
Radial gap size	ΔR_l [cm]	15	15	15	15
Location of backfilling	λ [m]	5	5	5	5
Dimensionless products					
	L/R [-]	2.00	2.00	2.00	2.00
	f_c/σ_0 [-]	0.29	0.30	0.25	0.40
	$(E\Delta R)/(\sigma_0 R)$ [-]	2.29	1.00	2.18	3.33
	$F_l/(\mu 2\pi RL\sigma_0)$ [-]	0.06	0.26	0.10	0.00
	λ/R [-]	1.00	1.00	1.00	1.00
	$K_l R/E$ [-]	0.90	1.80	0.60	0.72
	p/σ_0 [-]	0.07	0.14	0.05	0.04
Thrust force requirements					
Requires thrust force	Fr [MN]	74	368	194	0
Installed thrust force	F_i [MN]	150	150	150	150
Lining loading					
Ground pressure	p [MPa]	0.6	1.4	0.7	0.3
Bearing capacity	$p_{max} = d_l f_{c,l} / R$ [MPa]	1.2	1.2	1.2	1.2

Above: **Figure 4, longitudinal profile of a fictional tunnel (application example)**



Left: High cover tunnels such as West Qinling, China are host to a range of problems from squeezing ground to falling rock. Shown are ground support systems for the Chongqing metro

the tunnel section B (Figure 4) is critical and requires countermeasures such as, for example, higher quality concrete (i.e. a higher uniaxial compressive strength fc,l) for the segments in question.

In the same way, other calculations can be carried out very quickly for the other tunnel sections (A, C and D in Figure 4), thus allowing the critical tunnel sections (which are marked in red in Figure 4) to be identified rapidly.

Furthermore, a rapid sensitivity analysis could also be made in order to take due account of the fact that the intensity of squeezing may vary significantly even within a given tunnel section (for which constant material parameters may have been assumed a priori).

Closing remarks

The nomograms introduced in this paper for assessing the required thrust force show in a condensed form the statical conditions that have to be fulfilled in the design of a TBM in order to avoid jamming of the shield in squeezing ground.

When applied together with the extensive collection of TBM technical data presented in Ramoni and Anagnostou (2010a), which reviews the state of present-day TBMs, they enable quantitative statements to be made concerning the feasibility of a TBM drive as well as the effectiveness of potential design or operational measures (increase in the installed thrust force, reduction of the shield length, overboring, lubrication of the shield extrados).

The design charts for assessing the ground pressure acting upon a segmental lining enhance the set of decision aids available to the planning engineer.

Of course, the nomograms cannot eliminate the uncertainties associated with ground parameters and ground behaviour. Such uncertainties are intrinsic to every geomechanical calculation.

In the planning phase, the tunnelling engineer deals with this uncertainty and utilises the computational results as a decision aid for his risk analysis. In this respect, the nomograms represent a powerful tool for decision-making in the design process.

The correctness and suitability of the methodical approaches and decision aids briefly presented in Part I and Part II of this contribution – a detailed description can be found, for example, in Ramoni and Anagnostou (2011a) – have been proven through their successful application in a series of real world projects involving TBM drives in squeezing ground. For example, during construction of the Faido Section of the Gotthard Base Tunnel in Switzerland as well as of the Uluabat and Eskisehir–Kosekoy Projects in Turkey, in the planning phase of the Lake Mead No Three Intake Tunnel in the USA and the Bosslertunnel in Germany and also in the tender design for the El Teniente New Access Tunnels in Chile.

Acknowledgments

This paper is based on upon the research project 'Design Aids for the Planning of TBM Drives in Squeezing Ground' (Ramoni and Anagnostou, 2011a), which was carried out at the ETH Zurich, supported by the Swiss Tunnelling Society (STS) and financed by the Swiss Federal Roads Office

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The new face of Caterpillar Tunneling

In 2008 construction equipment giant Caterpillar bought TBM manufacturer Lovat. For the following few years many in the industry watched and waited to see what might become of the Canadian firm. In his first interview since the takeover Klaus Ukens, the new face of Caterpillar Tunneling, talks with Jon Young

Klaus Ukens

Klaus Ukens graduated with a diploma in mechanical engineering from University of Applied Science in Luebeck, Germany. His career started in France with Liebherr in designing and testing fabrications for mining excavators after two years with the German Navy in the Baltic Sea.

Four years later Ukens joined Caterpillar in Germany for a newly founded JV which developed the first Caterpillar designed mobile excavator. Here Ukens worked closely with Caterpillar's excavator design center in Japan and developed his first patents. He then moved to France to develop a new robot welding line before he became engineering and field service manager first in France and then in Belgium.

Later Ukens moved to the United Kingdom and led Caterpillar's Telehandler business, where he developed a global alliance with JLG, the world largest telehandler manufacturer.

In 2006 Ukens moved to North Carolina and led Caterpillar's small wheel loader and bulldozer business before he developed a global alliance with Wacker Neuson, which builds mini Excavators for Caterpillar.

In 2010 Ukens moved to Toronto and became Vice President for sales, marketing and product support globally at Caterpillar Tunneling.

The name of Lovat was a good selling point in many areas and had many fans. Why did Caterpillar decide to drop the name rather than using it as a trading name?

The name Lovat has been a strong name in the tunnelling world for nearly 40 years and has tunnelled more than 2,200km in 25 countries on six continents. At the same time Caterpillar is a Fortune 50 company with a globally recognisable brand, which has been a global market leader in many industries including construction for the last 87 years. The dual branding transition of 'Lovat a Caterpillar Company' was in place in 2010-2011 and in February of 2011 the name change to Caterpillar Tunneling Canada Corporation was officially realised.

Customers will realise the same 'DNA' in the Caterpillar Tunneling equipment reflective of everything that made Lovat a strong partner but fortified with Caterpillar processes while retaining the capable talent

Left: The Caterpillar Tunneling head quarters is split across a couple of sites, including the former Lovat factory, in Toronto, Canada

that made Lovat strong. The decision was in part driven from our global branding team who has the responsibility of protecting the Caterpillar brand worldwide but also to show the Caterpillar investment and commitment to construction both above and underground.

Are there plans to exploit Caterpillars strengths and tie up with other production lines such as the tunnel-modified excavator and dump-truck range?

Caterpillar has a vast global footprint of manufacturing and local dealer representatives in nearly every country in the world. The Caterpillar Tunneling product has been historically sold to customers directly but in places where involvement of the local Caterpillar dealership has added value we are exploring leveraging those relationships on a selected basis. This approach enables the possibility of equipment bundling between TBM's and more traditional surface construction equipment for an end user that desires the entire package from a single reliable source.

There are areas where the broader Caterpillar services have been and will continue to be leveraged to provide TBM customers with additional cash flow solutions. Caterpillar Financial has partnered with Caterpillar Tunneling to enable term financing options and in some cases even a lease or rental option in addition to the traditional TBM direct purchase or purchase with an optional buy back.

The Lovat factory has been massively expanded since joining Caterpillar, what has been the scale of the overall investment in the outfit?

The scale of the investment has been in the tens of millions of US dollars since the acquisition in 2008 to expand and tool up the facilities for more efficient workflow and increased production capacity.

The investments include improvements to the logistics flow within the facility. The machines are now built on an assembly line style system starting at one end of the factory and finishing at the other. To speed up buid time several major purchases were made including a Waldrich Coburg vertical turning machine, which allows the factory to deliver a metro size machine possibly months faster; a Union horizontal boring mill with an eight meter capacity; new computer numerical control machining centres that massively automate the machining of many parts; a 200t crane plus additional new cranes to carry large size components about the facility; An added refurbishment building (1,400sq.m) adjacent to 441 Carlingview Plant (32,050sq.m) dedicated to remanufacturing used client TBMs. Investment includes a rail connection between the two buildings, wash bay with retractable roof and an indoor/outdoor crane that will pick a TBM from the back of a truck; and a new manufacturing logistics centre facility (MLC), which is a 20,440sq.m facility with light manufacturing including cutting tools and production of the large CAT Buckets for the Model 994 Mining Wheel Loader, logistics, large Spare Parts Inventory. State of the art paint booth and new services lines set-up.

In addition, Caterpillar has begun a disc cutter development program utilising proprietary tough steel rings from Caterpillar and a similar ripper tool development, using Caterpillar's tough steel.

Lovat had a good name for EPB workhorses but was perceived in some quarters as not being up to the tougher jobs. What is being done to counteract this, and to be known for a full-range of TBMs for all ground conditions?

Lovat and now Caterpillar Tunneling have been seen as the right partner for the tough jobs. We have TBM's in operation from the 1970's which have been rebuilt three or more times. It is the rare case where a former Lovat and now Caterpillar Tunneling TBM are utilised for a single job. From a design perspective our machines are built to be rebuilt and differentiated by comparatively robust components in key areas including but not exclusively limited to the bearing design life.

There have been several recent examples of former Lovat now Caterpillar Tunneling TBM's conquering ground, which was not able to be navigated by competitors. The most blatant example was Brightwater in Seattle where our breakthrough was into the hull of the stranded slurry machine. Other examples include John Holland in Australia and CRTG in China where we are overcoming tough ground that our competitors were not able to navigate.

With regard to the question about full range of TBM's, we have demonstrated our expertise in EPB in mixed ground and under pressures above seven bar. With the recent successes with EPB in ground that slurry technology was less successful it has fortified our position that EPB is the more flexible and total cost solution to the end user and the technology we will continue to advocate. With that said we have quoted and built slurry machines in the past and where best suited for the geology and at request of the client we have that capability. In rock Caterpillar Tunneling continues to offer and manufacture both single and double shield machines on a regular basis. In addition Caterpillar Tunneling offers pipe jacking machine larger than 90 inches.

There is also a rumor going around that Caterpillar is only interested in 'off-the-shelf' machines with no project modifications. Is this true?

Always interesting the root of a rumor and how far the telephone game gets you from the truth. Appreciate the opportunity to dispel any concern. All of our tunnel boring machines are made to order. It all starts with the geology and client requirements. Those are examined by our seasoned applications team who then advise the client, their consultants and our own internal engineering staff on the best solution at the lowest cost to conquer the geology and achieve the project goals. When technical proposals are prepared in the initial stages some examples of previous successful designs are shared for reference, this is not in any way a limitation of the possible offerings. While we have standard configurations on construction machinery above ground with set options, the nature of TBM operation underground does not allow standard offerings. With the new edition of the Waldrich and Union equipment it will help us achieve even greater flexibility as well as increased production capacity.

With that said we are working to standardise subcomponent offerings of our machines where appropriate to help lower costs and better delivery times in the aftermarket to maximise TBM uptime.

The intention with this activity is to leverage all of our past experiences with designs and suppliers to formulate the best of breed solutions leveraging that strong history of successes but also the broader buying power of the Caterpillar organisation.

In addition to this we are introducing innovative solutions from broader Caterpillar like incorporation of the unique metallurgy of Caterpillar 'Tough Steel' used in tractor sprockets into our cutting tools. The performance of our tough steel disc cutters benefit from this unique

Above: Ukens says there have been several recent examples of Caterpillar TBMs conquering ground which was not able to be naviagated by its competitors

metallurgy as the steel is harder but less brittle to elongate time periods between cutter changes.

Lovat had made big inroads into the Russian market. Now that the new organisation will be seen as part of an American conglomerate rather than a Canadian company, is this affecting their marketing there and in the neighboring region?

Even though head office is in the USA, and TBM Manufacturer is in Canada, we are a company that serves the world. Caterpillar is making sustainable progress possible throughout the world regardless of the borders to help build infrastructure to improve the quality of life today and tomorrow.

We have always had a strong relationship with our fellow Russian clients. Since the Caterpillar acquisition of Lovat we have taken significant steps to grow those existing relationships and build a team that is now located in Russia to help with sales and product support in the region. The Russian market represents a significant opportunity and now after the elections the hope is that any hesitation to invest in approved projects will be reinvigorated as economic stability returns to the region.

We currently we have some 20 TBM's operating in Russia and are actively supporting these machines and our Russian clients with parts and service to maximise their availability and our clients possibility to realise additional business as the region continues to invest in infrastructure.

Many of the major TBM manufactures have opened factories in China to better compete for contracts, what is Caterpillar's strategy for the region?

With all the recent investment in expanded facilities within North America the initial intention is to maximise the production capacity within our primary facilities. We pride ourselves on our quality and workmanship including in-house testing with clients present prior to shipment to ensure confidence in the quality product that we are producing and components we are sourcing.

With that said the Chinese market is a massive one, which without a local footprint is difficult to effectively compete in. We have machines in operation with BUCG and CRTG in China currently. Historically we have manufactured in China with select joint venture partnerships where needed and will continue to utilise this option when necessary to be competitive in the local Chinese market.

On a broader scale Caterpillar is currently operating 13 Cat factories in China so we are no stranger to the region. In the future when we are ready to expand Caterpillar Tunneling operations within China we can leverage off of the existing factories and local dealerships to broaden our footprint in the tunneling industry.

Present and future state of UK tunnelling

Outgoing chair of the BTS Bob Ibell looks at the recent achievements of the UK tunnelling industry and the current state of works

We have a sizeable amount of tunnelling going on in the UK, including waste water project the Lee Tunnel and the power cable National Grid Tunnels coming on the back of completion at the Brighton sea outfall. The Crossrail tunnelling contracts are all placed and tunnelling began last month.

It can be argued the tunnelling boom has begun. But for it to continue a great deal of education is needed before there is an informed, honest and constructive dialogue between the industry and policy makers.

As tunnellers we are used to dealing with the challenges of the ground and, without chancing my arm or sounding smug, I might say that we have become better at this.

What we find difficult to deal with is the politics, bureaucracy, vested interests, local agendas and risk-averse bankers who will take enormous financial risks but run a mile from construction, let alone tunnelling risks.

These stakeholders influence the way that projects are developed, funds procured, even the way the works are specified and supervised.

Focus on quality

Although we have gone forward technically we do not seem to have learned all the lessons of Channel Tunnel Rail Link (CTRL), of the Heathrow collapse and of the teachings of Latham and Eagan's 'Constructing the team'.

We have not moved together, if anything we have moved apart. The team ethic is not very prevalent in some of the tunnelling projects despite the recognised benefits of collaborative working.

Some of our clients are beginning to understand this and are making determined efforts to realise the benefits by changing their ways. Others procure in a modern way but are using old-fashioned thinking and it is this that makes the difference. I was pleased to see chief construction advisor to the Government Paul Morrell's comment that "clients knowing how to ask for what they need is the key to efficiency savings and consequent cost savings."

It will be interesting to see if that is picked up.

Over the last couple of years we have also had informed thinking from Infrastructure UK (IUK) and the National Audit Office. The first conclusion of the IUK report is that the UK contractors need a consistency of workload to invest in people, technology, skills and development.

UK contractors would not agree that we are there yet and we will not get there until we elevate quality (in its widest sense) to the principal selection criteria. If we concentrate on quality and performance in a collaborative manner, cost minimisation follows.

The problem is how to develop the mindset and environment in which a strategy of this nature can be realised.

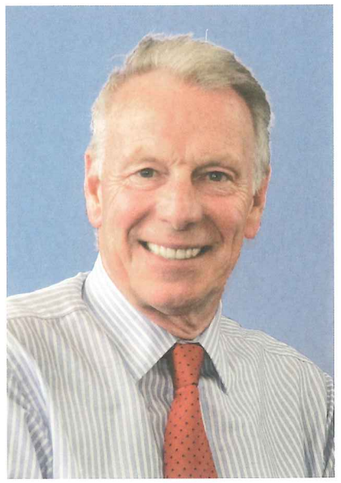
Working together

Collaborative working is important because it can swing the emphasis onto to performance and capability and with a global tunnelling boom competing for UK resources we must maintain standards of education, training and best practice.

We need to have managers who understand tunnelling. We must not let corners be cut due to aggressive costing.

Quality in its widest sense must remain the maxim. Quality is of course one of the main contributions made by the BTS, along with education, information and identification of best practice.

We have moved forward in the BTS in the last two years, enhanced the BTS reputation, increased the membership, provided more services, become more inclusive and drawn more members into the activities of the society.



Above: **Bob Ibell, outgoing BTS chair**

Establishing the sprayed concrete lining working group, improving the website, developing teachers' packs, improving the courses in design and construction and health and safety, promoting debate, producing authoritative documents such as the 'Monitoring Guide', the BS 6164 update, the 'Guide for Best Working Practice in High Pressure Compressed Air', developing registration proposals for tunnellers, all help the profile of the BTS in the tunnelling world and make a contribution to the wider society.

The profile of the BTS in the corridors of power is another subject, but one under current debate. The role of a learned society is important in this respect but unclear.

This debate will develop because the government at last seems to have realised the benefits of investing in infrastructure, while the industry seems to lack a coherent voice.

Incoming Chair of the BTS Damian McGirr looks at the future challenges and opportunities for the UK tunnelling industry

In the UK we have a number of tunnelling projects either under construction or about to commence. These include Crossrail, Lee Tunnel, Preston Unsatisfactory Intermittent Discharge tunnels, London Underground station upgrades, National Grid and UK Power Network cable tunnels to name just a few. Over the past few years there have been a number of infrastructure projects under construction that incorporate a significant amount of tunnelling, however what has often been missing has been the planning and further investment in future projects to provide a continuity of workload.

Driving a change

Investment in infrastructure appears now to be high on the political agenda, and there are several major infrastructure projects being considered that will include tunnelling work. A careful structuring of these projects can create a steady workflow for the industry. Principal amongst these are:

- The recent announcement by the Government to proceed with the construction of High Speed Two from London to the West Midlands for delivery in 2026 with over 30km of tunnels;
- News from Scotland that Scottish and Southern Energy (SSE) is considering a new hydro scheme near Loch Ness;
- The plans for up to eight new nuclear power stations in the UK, which will include significant amount of tunnelling and associated work;
- Further cable tunnels from both National Grid and UK Power Networks over the next 10 years;
- Proposals from Transport for London to further explore a potential crossing of the River Thames at Silvertown to supplement the existing Blackwall tunnel. Another road tunnel is one of the lead options under consideration;
- Upgrades on the London Underground network including Bank Station;
- The long-term management of Higher Activity Nuclear Waste;
- Not to mention the many other smaller but nonetheless vital tunnelling projects that are undertaken around the UK

But not all projects may come into fruition. There is a momentum building in support of the development of underground space; but there is still uncertainty in whether they will make it to construction and if they do, what the time frame might be.

Creating a continuity of workload will depend on two fundamentals: investment from both the Government and the private sector; and policy from central and devolved Governments to place the development of underground space firmly on the planning agenda as is now done in Hong Kong and Singapore.

Despite these difficult economic times financial investment has been forth coming as the Government has pledged funds, sometimes as part of economic stimulus packages. But more needs to be done by policy makers to ensure that at planning stage the viability of underground alternatives is considered.

The tunnelling industry also has to play its part. We as the UK tunnelling industry and through the BTS need to ensure that tunnelling has a continued and increasing role in the development of major projects through the promotion of tunnelling as safe, sustainable and cost effective.

The recent work by HM Treasury unit Infrastructure UK (IUK) into understanding the cost of infrastructure development in the UK was an important milestone in demonstrating that our industry can effectively deliver major projects.

Capitalising on this, an industry 'pipeline' has been developed to highlight future projects that will help remove some of the peaks and troughs in workload that have beset our industry.

The BTS is involved in supporting IUK in its work and has contributed by looking at the cost of tunnelling in the delivery of infrastructure projects. This support needs to continue, but we also need to increase our exposure to policy makers throughout the UK to ensure the development of underground space is firmly on the agenda when major infrastructure is being considered. The tunnelling industry has a role to play in demonstrating the business case for tunnelling as a viable element of major infrastructure projects. This can be done by ensuring that we can demonstrate an understanding of turn out costs and a sound approach to risk management in the same way as other sectors do.

We need to demonstrate value through the delivery of the current schemes being constructed in the UK. This will demonstrate that we have both the design and construction expertise within the UK to allow us to make the case for that tunnelling should be central to future infrastructure development and build upon on recent successes. As part of this we need to ensure that we demonstrate the high level of professionalism and competency that we undoubtedly have in the UK tunnelling industry.

Above: **Damian McGirr, incoming chair**

Role of the BTS

The BTS will be looking at all of these issues in the coming months and years to ensure that we can have a greater exposure to decision and policymaking. It will spearhead the education of our workforce and ensure the UK keeps in line with global best practice. It will initiate a registration process for tunnellers.

As I write I am on my way to the University of Warwick to discuss further development of the MSc course in underground construction for the 2012/13 academic year and beyond to help ensure that we have the engineers that we will need for the future support and development of our industry.

More joined up thinking is required within our industry to realise that successfully delivering the current projects on time and within budget will prove to investors and decision makers that UK tunnelling is a sound investment. This confidence will secure future work in the many projects under discussion. Failure to secure a steady workload could lead to an exodus of tunnellers from the UK as the global tunnelling industry is in boom and demand is high for skilled miners.

The coming years will present new challenges for the industry and the BTS will take the lead in developing closer links with central and devolved governments to ensure a future for our industry.

Crossrail countdown

With the first Herrenknecht TBM launching as T&TI goes to press, Alex Conacher takes a look back to site visits in early February as segment production had just begun, and the machines were being assembled in the west London mud

A kilometre-long stretch of mud and machinery forms the worksite leading up to the Royal Oak Crossrail portal as *T&TI* visits in February. As narrow as 20m in places, conditions are tight, with single-file walkways in places. The A40 flyover juts out along the north of the site and surface rail skirts along the south.

As the visitors are lowered by cage lift from the site office near the flyover, the roaring noise turns out to be coming from a skate park echoing off the underside of the elevated road.

The first machine is nearly assembled and waiting to be taken away from the Westbourne Park site (the west end of the worksite), through the Royal Oak eastern end of the site, and towards the Royal Oak portal at the extreme east.

The BAM Ferrovial Kier (BFK) JV's workforce is 100-strong and began site preparations in November 2011. The contract award for the 6.2km western tunnels from the Royal Oak portal to Farringdon was announced in December 2010 along with a contract for access shafts and SCL work at Tottenham Court Road and Bond Street. The combined value was GBP 500M (USD 787M).

The machines

The Herrenknecht TBM set to execute the first drive for the Crossrail project is approximately 85 per cent assembled says Derek Whelan, BFK shift manager. "The cutterhead itself is about 99 per cent complete. We're on target to kick off on 21 March with no delays expected.

"We'll move the first TBM down to the tunnel eye on 16/17 March over a period of 24 hours. The second machine should be fully assembled by the end of March, with transition to the portal on 14 April and a launch towards the end of that month. There's a four-week stagger on the two drives."

Mammoet was contracted to move the machines to the tunnel eyes via 500t cranes. Whelan and BFK tunnel agent Alfonso Chicharro point out a small bridge that runs overhead and perpendicular to the route the TBM must take from the back of the site to the portal.

Mammoet will raise the bridge on jacks for around 10 hours at a time. The jacking forces required are not particularly large.

The TBMs themselves are 7.1m EPBMs. Once lined, the Crossrail running tunnels will have a 6m internal diameter. During a visit to the Herrenknecht TBM factory in Schwanau, southwest Germany in December, Ralph Lickert, a Herrenknecht project manager for Crossrail told *T&TI*, "This is a very compact machine. You can see from walking through it that there isn't much room. It is also very powerful with over 55,000t of thrust and a high main drive torque [of 9,800kNm].

"The belt scales are also of the highest achievable quality and are provided by [Australia-based] Control Systems Technology which was the only company able to meet the requirements."

The machines are expected to carry out a 100m+ advance each week, removing 20,000t of spoil in the process.

Main image: TBM assembly at the Royal Oak site
Right: Scissor lifts load segments for transportation to the storage yard.
Photos courtesy of Crossrail

Above: Some 213 CBE moulds are needed for segment production by the BFK JV

New regulations

British standard 6164:2011, clause 14.12 requires refuge chambers in UK tunnel projects. The 2011 update is applicable to this project. Donald Lamont, principal of Hyperbaric and Tunnel Safety and member of the Crossrail Engineering Expert Panel says, "The standard does not directly address TBM safety but does so through reference to EN 12336, which is the current CEN standard for TBM safety. EN 12336 is to be replaced in due course by prEN 16191 – the draft revised CEN standard for TBM safety, which will require a refuge chamber on a TBM.

"The Crossrail TBMs are not the first in the UK with chambers – the Lee Tunnel TBM has one. ITA Working Group Five is also preparing guidance on the specification for refuge chambers – their equipment duration and so on."

Update and schedule

On 22 February a Crossrail spokesman announced that the first machine had been completed. Andrew Wolstenholme, Crossrail chief executive adds, "The first Crossrail TBM is due to undergo testing ahead of the start of tunnelling. Work is underway to assemble the second TBM."

Wolstenholme adds that following the second TBM launch in April, "later this year a further two TBMs will be launched from Limmo Peninsular in the Royal Docks that will travel a total of 8.3km (westwards) towards Farringdon via Canary Wharf, Whitechapel and Liverpool Street.

"Towards the end of 2012 another two TBMs will begin construction of the south-east section of the route, launching from Plumstead portal in the south-east and travelling a total of 2.6km to construct the Thames Tunnel."

Managing manpower

The drives from Royal Oak to Farringdon will advance in a two on, one off three-shift pattern with 12 hours to a shift. Crossrail's western tunnels project manager Andy Alder says, "The important thing is managing fatigue. You can do this if you know where people live and can make sure they are not travelling a long distance before and after working, and that is what we are doing here.

"Some people in the industry have given the opinion that you should run eight hour shifts rather than 12. The simple fact is that there just aren't the manpower resources in the industry for eight hour shifts unless you take on less experienced people."

Moulds, segments and production

The BFK JV is supplying its own segments for the western tunnels at a new purpose-built factory at Old Oak Common in west London. The factory will be replaced by a major Crossrail depot upon an end to production in spring 2013.

Bob Wagstaff, BFK segment factory manager, says, "After this we have a duty to get maximum value from the moulds. We will try to find a comparable diameter project for this, but the industry is not always the best at learning from itself – we will probably find a job that is 0.05m out."

It was incredibly cold on site as production began in the first week of February. During the night following *T&TI*'s visit in the second week of the month, teams say they are preparing for temperatures as low as -5°C.

Wagstaff explains mould selection: "A carousel system brings the sides up and the middle down. Once it's out of the curing chamber at 60°C you have to look after the segments, and you just can't do that in this cold. With our static moulds, all of the segments are perfectly within tolerance."

Wagstaff adds, "We have a seven minute cycle time and it is 18 hours before we de-mould normally, though a bit extended due to the cold. Strength is 30N at 24 hours and easily 20N after 18 hours. We reach 58N after seven days."

In total 213 moulds have been manufactured by CBE for the project. Segment stockpiles need to be maintained at six weeks of the consumption due to tunnelling rate. Wagstaff estimates this will be approximately five or six hundred rings, but that they will probably exceed this and reach the 2,000 to 2,500 stockpile capacity of the site.

Segments are in a seven plus key arrangement. They are tapered, and moulds colour coded with red moulds producing right segments and blue for left. An internal micrometer is used to check the width of moulds and depths are checked by vernier scale. Segment width and depth is also checked by vernier.

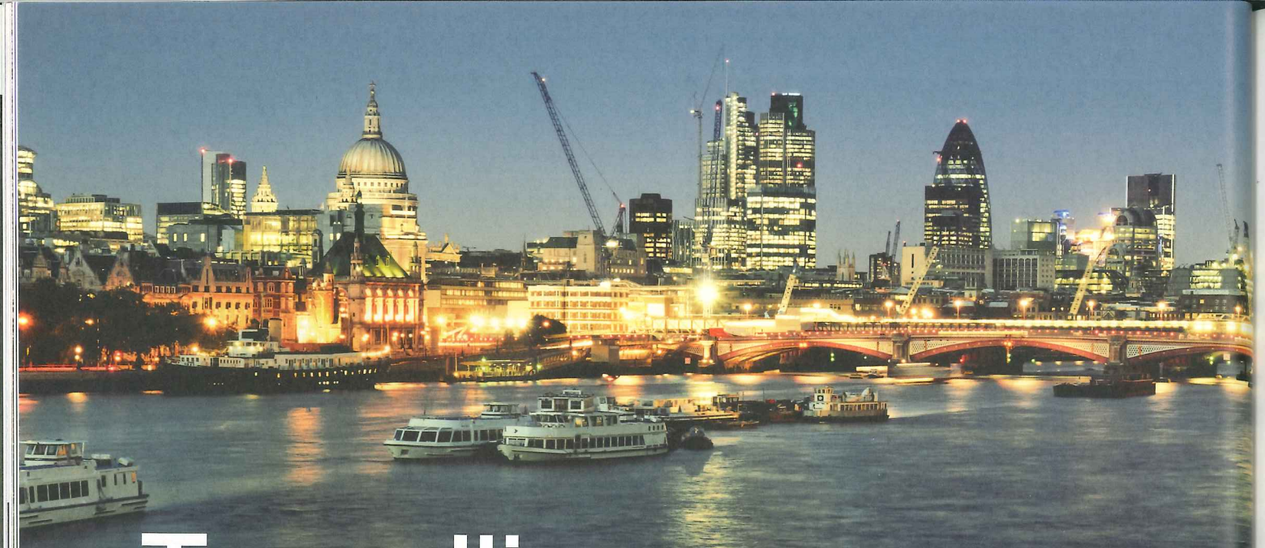
EPDM gaskets are used, with combined hydrophilic in some areas.

Scissor lifts are used to lift the segments. Wagstaff says that he favours this method over vacuum, which he views as time consuming and that he likes to "keep the operation as simple as the team can make it". The cost of all moulds, lifting and turning gear from CBE was EUR 3.6M (USD 4.84M). Each mould has an identifying code that is cast onto every segment. The date is sprayed next to this giving each segment a unique identity.

The mix

"The basic concrete mix is based on the High Speed One specification," Wagstaff tells T&TI. "But it is a stricter specification – it's High Speed One and a little bit more. We are using a limestone aggregate and 40kg of powder in a 70/30 ratio. Some 30kg/m3 of Dramix steel fibres with hooks go into the mix and an increase of polypropylene fibres was required – 1.25kg/m3 passed the fire test."

A BFK spokesman said 1-2kg/m³ of Propex poly fibres were used. Bekaert manufactured the batching plant, which has a planetary mixer system.



Tunnelling induced settlements in London clay

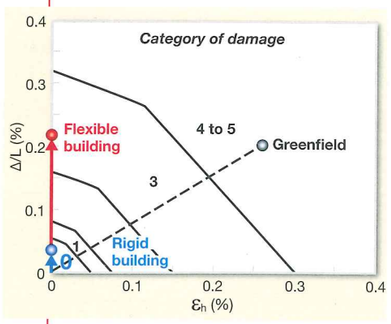
Robert Mair of Cambridge University, Jamie Standing of Imperial College and Keith Bowers of London Underground presented three papers on the effects of settlement in London Clay at a joint meeting of the BTS and British Geotechnical Association in January

The basic concept of effects of tunnelling on buildings describes the transverse settlement trough caused. The trough conforms to a classical Gaussian equation that can be derived from a fundamental parameter in settlement assessments, the volume loss. A volume loss of around one per cent has been established in many cases in London Clay.

Volume losses within the 1.5km EPBM-bored London Clay section of HS1 contract 220 were nearly always less than one per cent. A number of factors control volume loss, but controlling the face pressure is an important element in controlling ground movement. Mixed ground conditions can give rise to fluctuations in face pressure but London Clay is more uniform and it is easier to keep face pressures broadly constant.

For London Clay there is some influence of TBM chamber/face pressure on the volume loss in EPB tunnelling. If for seven quite well instrumented cases, volume loss is plotted against the average face pressure, divided by the total overburden pressure at tunnel axis ($\sigma v0$), then there appears to be a relationship. As the ratio of face pressure / $\sigma v0$ rises, volume loss lowers (Mair, 2008).

The depth of the tunnel will have an influence, but what can be seen is that in London Clay we should be getting reliably less than one per cent volume loss with well controlled EPB tunnelling.



Left: **Figure 1, graph showing categories of damage**

Structural stiffness

If a building is considered in relation to the settlement trough, the deflection ratio and horizontal strains are important factors to consider. The stiffness of the building modifies the settlement shape and it may not experience much deflection ratio. A modification factor (M – the deflection ratio of the building/greenfield deflection ratio) can be established. For a fully flexible building M=1 and for a fully rigid building M=0.

Centrifuge modelling tests have examined the modification factor in some detail. Structures of different stiffness and tunnels at different depths and positions in relation to the structure were idealised. If extracting fluid from the annulus of the modelled tunnel accurately controls volume losses, Greenfield settlement troughs can be produced which, with the addition of a flexible building, are similar. Increasing the stiffness of the building gives an increasingly stiff response to the settlement trough. The relative stiffness of a building (ρ^*) has been established (Potts and Addenbrooke, 1997).

This can be simplified for design purposes as ρhog and ρsag (Mair, 2011). If the centrifuge results are plotted on a graph of modification factors against the log of the relative stiffness of the building ρhog or ρsag , a useful 'band' for design can be seen, which is consistent with finite element analyses undertaken by Potts and Addenbrooke (1997) and Franzius et al (2006). A fully rigid response (M=0) is seen if ρhog or $\rho sag > 1$ or a fully flexible response (M=1) is seen if ρhog or $\rho sag < 10\text{-}4$.

The horizontal strains measured in a building are often negligible compared to the greenfield theoretical value of horizontal strain.

If a building is assumed to follow the greenfield settlement this can significantly overestimate the damage category. Assuming that the horizontal strain induced in a building is small reduces the damage category, and for a rigid building the category of damage reduces much further. The need for protective measures such as compensation grouting may often then be overestimated.

Drainage

With tunnelling there is an immediate undrained settlement, based on volume loss. If the tunnel acts as a drain there will be a long-term slow development of flow through the clay into the tunnel causing long-term settlement (the tunnel will also squat).

For old London Underground (LU) tunnels pore pressure can be zero at the lining rising rapidly with distance from the tunnel, with exceptions. The tunnel lining system's permeability is critical, particularly the grout. Older grouts often have a much higher permeability than modern. This can be due to long leaching and carbonation.

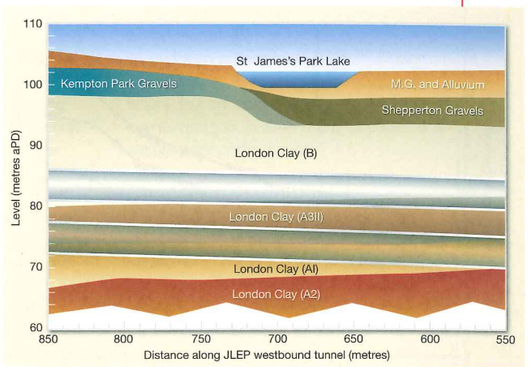
If a tunnel acts impermeably there will be very little long-term settlement. A long term dimensionless settlement (DS) can be defined (Wongsoroj, 2005; Mair, 2008), this would vary from zero for an impermeable tunnel to one for a fully permeable tunnel. If DS is plotted against the log of relative permeability (RP) tunnels with an RP<0.1 may be classed as impermeable and there will be no long term settlement. Those with an RP>100 may be classed as fully permeable and there will be significant long-term settlement.

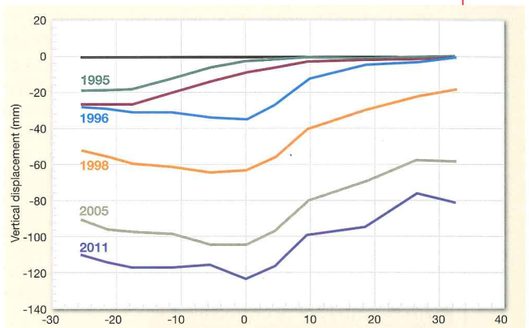
The initial ground pore pressures are a key factor to consider for long-term settlement. The degree of anisotropy of soil permeability is also important; the horizontal permeability of soil is usually greater than the vertical. London Clay permeability is highly variable.

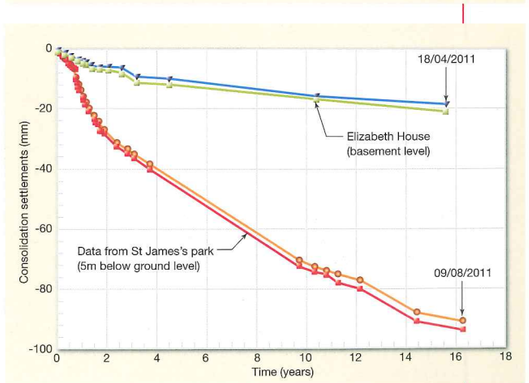
Identification of London Clay divisions resulted from studies on Jubilee Line works passing beneath St James's Park. Large volume losses were recorded. It was suspected that tunnelling had an influence but also that geology played an important role. The London Clay beneath Westminster can be divided into Unit B, Unit A3 (which is split up into two Units; A3ii and A3i) and Unit A2, which sits above the Lambeth Group. Each of these Units has a different structure and has a range of permeabilities.

For long term monitoring extending over a period of many years, the instrumentation and systems need to be robust and durable. Long-term settlements can occur up to 100m away from the tunnel works, which makes the positioning of a datum problematic. There are not only vertical movements to be measured but also horizontal displacements and pore pressures.

The magnitude of movements depend on: the type of ground (the more compressible the greater the likelihood of movement); the groundwater conditions; the presence of existing tunnels; the type of lining; the relative ground to lining permeability; time; relative consolidation and creep processes.

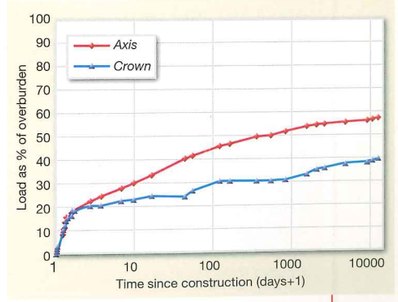




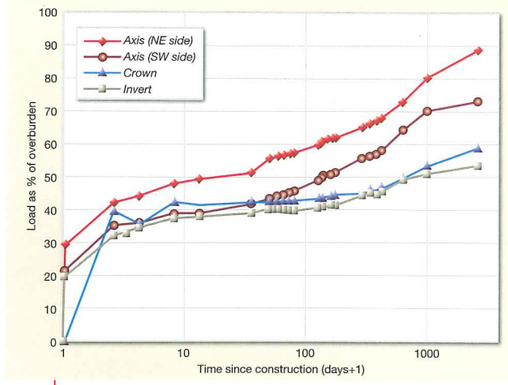


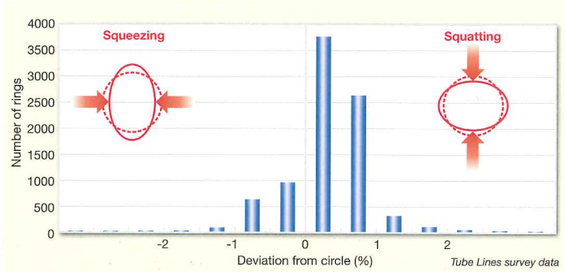
Cases

St James's Park is underlain by Units B and A3 and the tunnel was constructed with an open face shield with expanded concrete segments. The westbound tunnel was in Unit A3, with A3ii lying just above the alignment. The eastbound tunnel was in Units A3ii and B. The lining was permeable – a walk through the tunnel showed the tunnel lining to be wet in one Unit and then dry in the adjacent



Right, top: **Figure 2, Jubilee Line Extension London Clay Units; Right, higher: Displacement versus centre line offset; Right, above: Figure 4, Consolidation over time of St James's Park and Elizabeth House; Right: Figure 5, Increasing load as a percentage of overburden over time**





Left: Figure 6, Introducing load on invert and different sides of axis
Above: Figure 7, Tubelines surveys showed a tendency for London Clay tunnels to squat by around one per cent

Unit. At St James's Park there is almost a hydrostatic profile. Settlement profiles over time show a progressive deepening and widening of the trough with around five times the short-term movements recorded. Consolidation settlement continues for 16 years following construction.

The larger 8m-diameter CTRL tunnels at Dagenham were constructed in the Unit A2 by EPBM and grouted segmental linings. Consolidation movements took place within quite a short period of time with 12mm in the first month reducing quite drastically. The long-term settlements were of similar magnitude to the short term and took place very rapidly. The tunnel was located within the Unit A2, which has the highest permeability and allowed pore pressure to essentially equilibrate. As for St James's Park, this was a greenfield site with hydrostatic pore pressures and no other tunnels nearby. The smaller settlements recorded can perhaps be attributed to a grouted lining.

Monitoring for Elizabeth House on the JLE showed that cumulative settlements from running tunnels and cross over passage, constructed in sprayed concrete, are 4.5 to five times smaller than those at St James's Park and are levelling out. The reason is that this is not a greenfield site; the area is crossed by number of existing tunnels. The pore water distribution at this site shows a certain amount of under drainage compared to the hydrostatic

Questions from the floor:

Barry New said that for stiff structures, horizontal strains can only be ignored if the structure has a continuous foundation. If on pads, the pads move apart and horizontal stresses cannot be ignored. In addition, with reference to the reduction that relates to flexural bending, if a stiff structure is placed on top it does not bend much and the strains in that structure are small, but this relies on the asset owner accepting that his structure will act as a 'bridge' for the tunnel. In soil-structure interaction is slow; after decades a seemingly stable structure can break.

Robert Mair said that when New mentioned that the structure acts as a bridge it was implied that the ground moves away from beneath it and it is left spanning a gap. This isn't necessarily correct. What we know is that the building modifies the ground response and it is not the case that a large stiff structure such as the Treasury would span a large void formed beneath it.

David Norbury of David Norbury said although each site was different in terms of the amounts of movement and rates of movement, it seemed that they were similar and that there were continuing movements. Were the movements in the case histories actually carrying on for a long time and still continuing at comparable rates without dropping off markedly?

Jamie Standing replied that there were differences in the rates and some of the movements were diminishing. Comparing the extreme case of St James's Park and the contrasting Elizabeth House studies, the permeability of the lining systems were very different and there are still movements, but the rates and magnitudes are much lower. The rates and magnitudes are different and this is perhaps not surprising as the Elizabeth House tunnel was in the A3i Unit, which has a low permeability.

Peter Wright of Halcrow noted that long-term settlements have a wider trough than short term and asked if this is due to the fact that the horizontal permeability is greater than the vertical permeability and whether there would tend to be a further spread of consolidation settlement? What might the situation be in a more homogenous ground or ground with an emphasis on vertical permeability?

Jamie Standing responded that in most cases the ground is quite anisotropic. Studies show a ratio of 1:25, vertical to horizontal, which will certainly widen the trough. In the longer term the deflection ratio does not worsen and although there is a widening and deepening of the troughs, damage should not be excessive.

Stephen Pallant of Parsons Brinckerhoff commented that it is popular to use settlement contours to identify which buildings need to be looked at in detail, yet there is no direct mathematical relationship between the deflection ratio and a 5 or 10mm contour. Would it be more sensible to identify which of the buildings are most at risk by looking where the deflection ratio exceeds a certain value?

Robert Mair replied that it would but it is pragmatic to use settlement contours as a starting point. We must not just rely on settlement contours as there is a tendency to jump to the need for protective measures based on a greenfield assessment basis. We should be looking at the deflection ratio implied for the building and then looking at the stiffness of the building more than we currently do.

Keith Bowers added that the use of settlement contours to identify what it is you need to think about is required by LU's standards. The use of the contours is a quick first filtering exercise to guide us. Once the assets of concern are identified we would go into structure specific approaches.

Stephen Pallant said that if the worst area of deflection ratio lay outside a given contour then looking at settlement contours wouldn't identify the area you should be looking at.

Robert Mair stated that there could be a case where a building with a critical deflection ratio is outside the 10mm contour, but this would be unusual.

profile found at St James's Park. The Elizabeth House tunnels are also constructed in Unit A3i, the less permeable Unit. The lining is very different with St James's Park being permeable and the ones at Elizabeth House almost impermeable.

Long-term settlements measured at the Treasury Building for four years before it was renovated show a settlement of about 25mm, compared to the 30mm measured at St James's Park over a similar time period. Settlement took place regardless of the compensation grouting.

Long-term monitoring

Field monitoring in the long term is vital for understanding the effects of consolidation and creep and that more thought about who does the monitoring is needed. The long term response is dependent on a number of factors: the type of ground; the London Clay Units; the ground water conditions – whether hydrostatic or underdrained; the presence of any existing tunnels; the type of lining and the relative ground to lining permeability; and also whether there is just consolidation or creep as well. Creep plays a major factor and this should be considered for analysing long-term movements accurately. Long-term displacements can be several times greater than the short term, and the trough widths widen considerably as at St James's Park.

Long term settlements at Dagenham for the CTRL and at Elizabeth House were much smaller than at St James's Park. Long-term settlements are also evident for a structure that has been compensation grouted. It would also be useful to gain information on long-term horizontal movements so we can ascertain the long-term displacement field in conjunction with pore pressure measurements.

LU behaviour observations

Many of LU's tunnels are over 100 years old, in over-consolidated clays, with many elements that would not satisfy modern design requirements. These structures are usually robust, long lived and have low maintenance, with occasional failures, an opportunity to study long-term behaviour.

Changes in LU's tunnel structures include: changes in lining loadings due to tunnel excavation, other works or soil changes; deformation of tunnel linings by loading changes; groundwater change with recent concerns relating to perched aquifers; thermal changes such as heat generated by trains; and soil changes such as dessication or acid generation.

Data from an instrumented ring at Regent's Park shows that 35 years after its construction, lining loads are currently at nearly 60 per cent of overburden and are still increasing slowly. An instrumented ring at St James's Park shows that the lining load increases significantly during the first decade asymmetrically between 70 per cent and 90 per cent of overburden.

Circularity surveys by Tubelines found that despite uncertainty over build shapes, a large data set confirms that most London Clay tunnels squat by up to one per cent.

A consequence could be a slow change leading to equilibrium, possibly with 'locked-in' stresses, an example of which could be tunnel squat. Alternatively there could be slow changes, possibly at a reducing rate, which could lead to the onset of a progressive failure: an example is damage to an expanded pre-cast concrete lining first noted 30 years after construction, caused by movements due to soil desiccation increasing lining loads.

Such processes develop over decades, which means that determining when intervention is needed is difficult. Slow changes may eventually lead to a sudden failure. In London's clay tunnels these events may occur after many decades of satisfactory performance.

Change management

Despite the minimal maintenance, these structures don't necessarily exist in perfect equilibrium. There is change going on in much of the network that can give rise to changes later in the service life. A couple of those problems arose at about 30-40 years into the life of the structure, while another arose 100 years into the life of the structure. This would not necessarily be the time to expect this to happen.

LU needs to understand what the structures could be capable of and ensure they have appropriate systems in place to track any changes that develop.

Rapporteur: Simon Stroud

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Supporting Victoria

Render of station entrance

The UK's first use of jet grouting in conjunction with shallow sprayed concrete lined tunnelling and pioneering use of building information modelling are among the many innovations on London Underground's ultra-challenging Victoria Station Upgrade programme. Andrew Mylius of Mott MacDonald reports

From ground level downwards, London Underground's (LU) GBP 700M (USD 1.1bn) Victoria Station Upgrade is exceptionally challenging. The programme is designed to significantly increase the station's capacity, reduce journey times, improve emergency evacuation and provide step-free access for people with impaired mobility.

Victoria Underground Station serves the Victoria, District & Circle lines with two existing ticket halls. The upgrade will double the size of the existing Victoria Line ticket hall – referred to as the South ticket hall as it is located on the south side of traffic-choked Victoria Street. A new entrance and third ticket hall will be created on the north of Victoria Street, linked to the platform tunnels, the south ticket hall and the District & Circle line ticket hall by new passenger tunnels. Seven new lifts will provide step free access from street to platform levels.

Tight fit

The new ticket halls and tunnels are being built cheek by jowl with existing infrastructure – the site is crisscrossed by existing pipelines, sewers and power and communications cables. Construction will take place adjacent to or beneath the foundations of buildings. Secant piles forming the walls of the north ticket hall will be within 3m of the Victorian culvert carrying the River Tyburn. The passenger tunnel linking the north ticket hall to the Victoria Line ducks under the culvert and scrapes over the southbound Victoria Line platform tunnel with only millimetres to spare. An escalator squeezes between the twin bores of the north and southbound platform tunnels with a meagre clearance of some 300mm. Existing tunnels are relatively shallow. "We are threading the new passenger link tunnels under the District & Circle Line, which is only 2.5m below street level in some areas, and over the crown of the Victoria Line, which is about 14m below ground," says LU programme manager Glenn Keelan. This places the new tunnels at the interface between London Clay and overlying, water bearing terrace gravels. Jet grouting is being used to stabilise them, preventing disturbance to existing structures when tunnel excavation begins and creating an impermeable barrier to keep the new works dry. Jet grouting involves inserting a hollow drill bit like a hypodermic needle into the ground and injecting cement grout at pressure so that it mixes with surrounding material. "We have to get 2,500 jet grout columns in around everything that's already in the ground to

provide a stable and safe environment for tunnelling," Keelan states.

To manage all this complexity, the project team is using building information modelling (BIM) on a scale that is unprecedented in the UK. BIM is a process that incorporates 3D design, simulation and analysis, quantity surveying and a host of other tools, and provides a platform for collaboration. "LU initiated this approach because without a spatially accurate, fully co-ordinated 3D model it would be near impossible to visualise and co-ordinate the project," explains Mott MacDonald project manager Rob Dickson. "The model was an engineering requirement."

Victoria Station Upgrade is being delivered by joint venture contractor Taylor Woodrow-BAM Nuttall (TWBN) under a design and construct contract, with shared gain/pain. Consultant Mott MacDonald developed LU's concept design, helped steer the project through the statutory processes and is now working as the designer for TWBN.

Below: **Figure 3, Sub-street view of VSU. District & Circle Lines in bright yellow and green, Victoria Line in blue. Grey structures are existing works, new developments shown in dull green. Above ground structure is the existing mainline station**

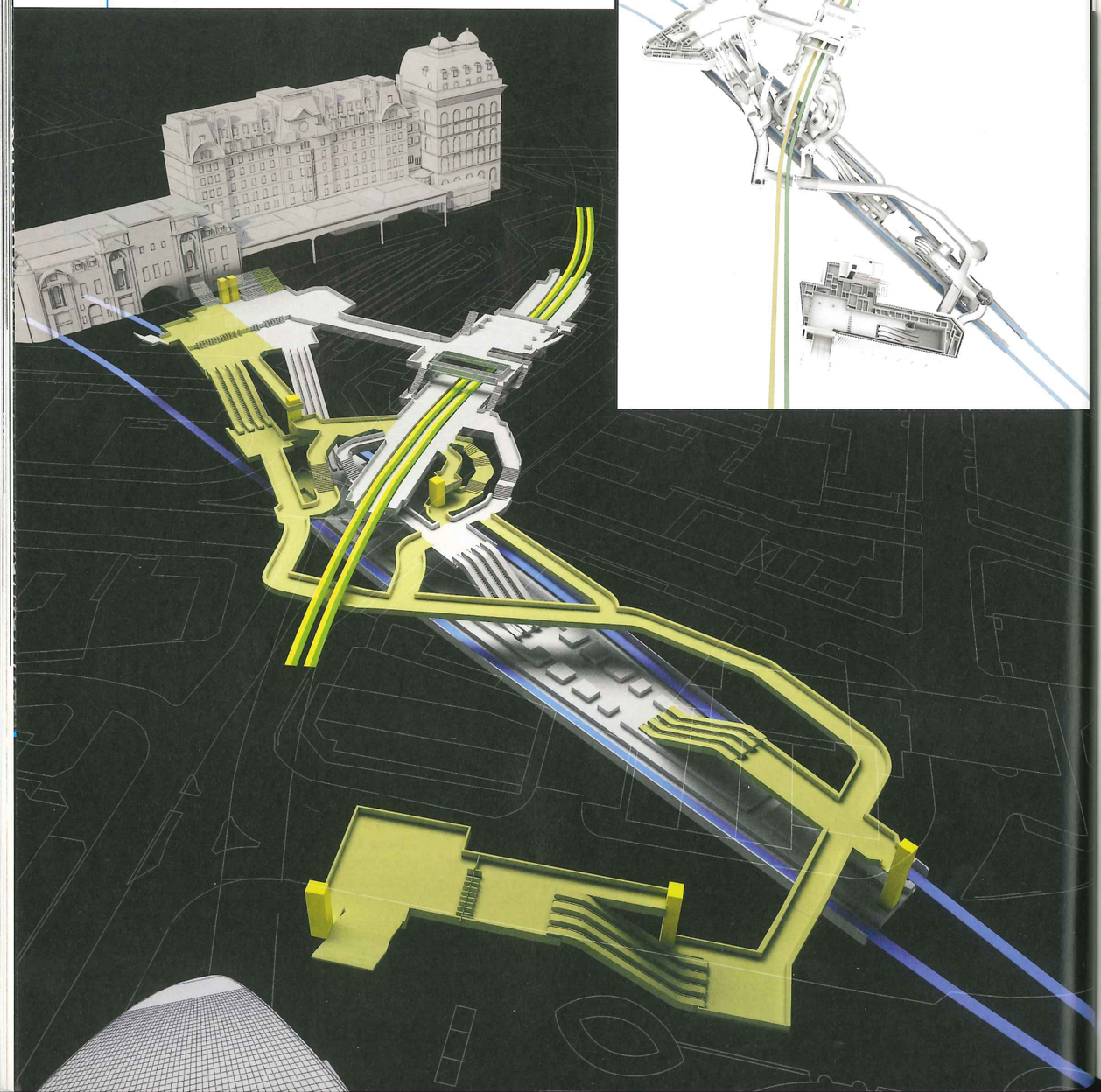


Figure 2, station layout showing District & Circle Lines in yellow/green and Victoria Line in blue

Construction is taking place smack in the middle of one of the UK capital's busiest transport interchanges. "We're carrying out major, complex civil engineering in a live environment." comments TWBN project director Bob Lloyd. "We've got underground and mainline rail stations and a bus terminus that are used by hundreds of millions of passengers a year – Victoria Underground station alone handles 80 million. We're surrounded by government departments, offices and shops. Nothing we do on this project can be allowed to cause serious disruption."

TWBN and ground engineering subcontractor Keller are relocating services and have started ground treatment, while in April secant piling for the first new ticket hall box and shaft begins. TWBN and Keller are operating from 12 handkerchief-sized sites, preparing the way for tunnelling while allowing people and traffic free movement through the area.

Tunnelling in terrace gravels

"Jet grouting has been used mainly for underpinning buildings in the UK," says Dickson. "Although it has been used to prepare loose, water bearing materials in advance of tunnelling in northern Europe, we think it's the first time that jet grouting has been used for this purpose, on this scale, over here."

Keelan adds, "Prior to incorporating the method, LU commissioned a trial on site in Victoria. Given the project complexities we felt it important to prove the method in situ and test it before the scheme went to public inquiry."

Lloyd says, "We're effectively creating a zone of weak concrete."

The grout mix is designed to achieve a minimum strength of 1MPa. but is expected to be stronger. Jet grout columns will form a solid block, creating typically a 2m annulus around the new underground structures. Jet grout columns will generally be 1.6m in diameter, each overlapping with its neighbours by a minimum of 150mm. However, to ensure required coverage is achieved, diameters of 1.4m and 1.8m will also be used.

"To get in around the existing infrastructure we've got columns raked in every direction," Lloyd says.

BIM has been used to record the location of existing LU and third party assets. Utilities are being relocated when necessary. "Once a clear path has been created, we're using the model to define the position, orientation and rake of the drill string, as well as to facilitate quantity take offs and setting out. Site preparation involves exposing existing utilities and installing protection sleeves so that the rig operators can drill past them with confidence."

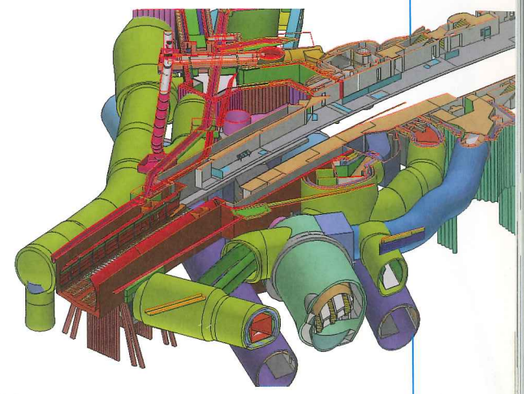
Interacting with existing tunnels

New tunnels will range in diameter from 4.5 to 9m. In the main they will be driven using back acting excavators and lined with sprayed concrete. The combined thickness of primary and secondary linings will be some 600mm.

Excavating a hair's breadth from existing tunnels and breaking into them presents a range of challenges. Jet grouting plays an important role by relieving load on the brick tunnels of the District & Circle Line and segmental cast-iron Victoria Line tunnels in position, says Mott MacDonald principal tunnel designer Steve Penfold. However, the new link tunnel connecting the North and South ticket halls changes section four times along its length as it negotiates neighbouring structures. "The proximity of other tunnels creates shear and bending forces that you'd normally counteract by designing a big, thick lining. Due to the spatial constraints here, we've carried out some very complex modelling. We've stretched the performance of the lining to the limit."

Where the link tunnel ducks under the District & Circle Line, sophisticated temporary works are required to provide support. "Initially it appeared that we'd have to take several possessions of the railway while we excavated underneath," says Lloyd. LU and TWBN have been at pains to avoid this. "We have looked at ways to minimise settlement risk, including ground freezing and box jacking. Installing a pipe arch is now considered the most cost and time-efficient option and reduces the impact on the operational railway."

At the north end of Victoria Station the Victoria Line platform tunnels converge. Work on the new tunnels will advance from a sprayed concrete lined shaft. "The shaft's cylindrical at the top but elliptical at the bottom to fit between the tube lines," Penfold says. Hemmed in on both sides, 17m of hand mining will be required to advance the tunnel out of the shaft and between the existing tunnels.



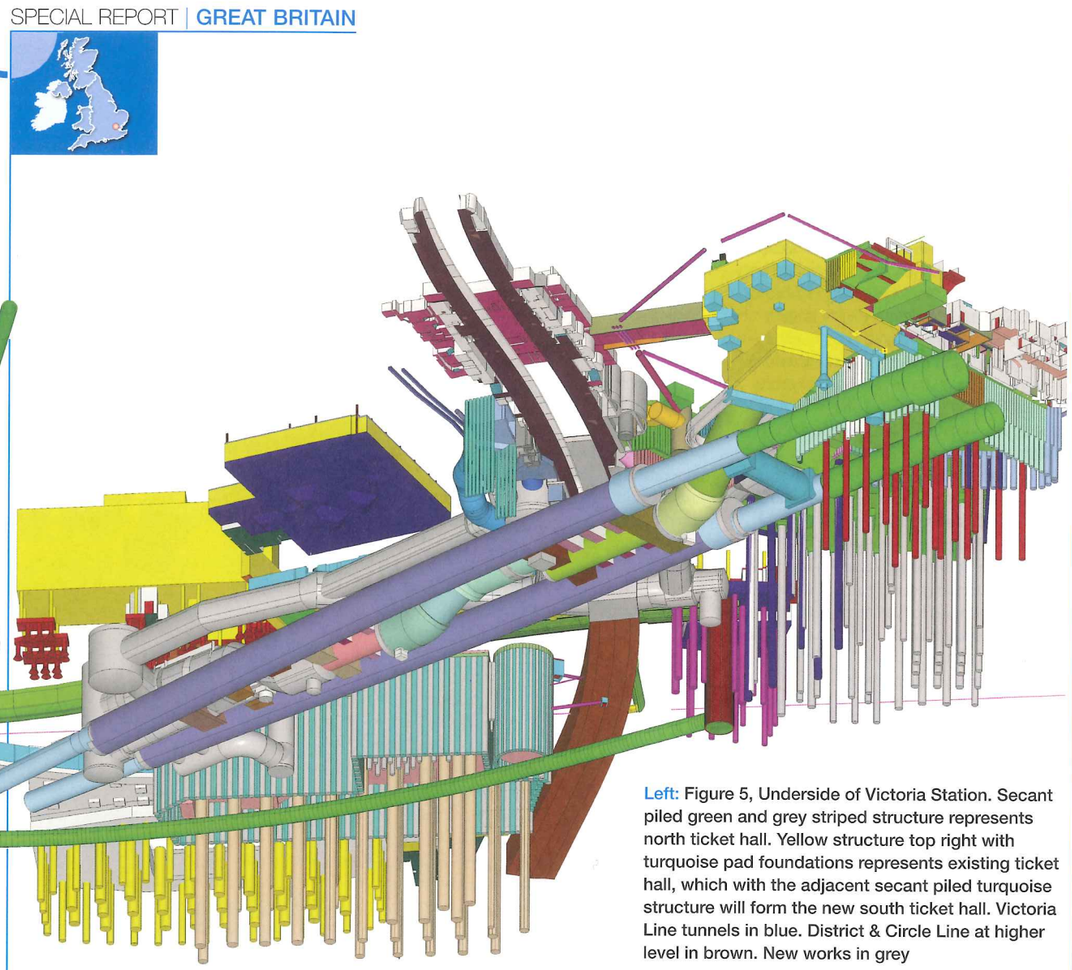
Above: **Figure 4, Tightly packed development. New works shown in green, box with cutaway top in bottom left shows District & Circle Line, dark blue tunnels are Victoria Line**

"We're saving every millimetre of space possible. The structural thickness of shoring frames will be less than half that of the primary and secondary sprayed concrete linings used across the rest of the project," says Penfold.

The square cross section achieved using hand mining also provides the same passenger capacity as a cylindrical tunnel but with a saving on width. Frames will be installed at 650mm centres. They will be in contact with the adjacent cast iron linings of the tube tunnels and connections have been designed to assure correct propping.

There are six adits connecting into the Victoria Line platform tunnels. "During break-through you're compromising the structural integrity of the existing tunnel. Traditionally you'd support it from the inside by installing temporary props," explains Penfold. "There isn't the space to do that

Right: **Cutaway street view of north ticket hall below Bresenden Place off Victoria Street**



Left: Figure 5, Underside of Victoria Station. Secant piled green and grey striped structure represents north ticket hall. Yellow structure top right with turquoise pad foundations represents existing ticket hall, which with the adjacent secant piled turquoise structure will form the new south ticket hall. Victoria Line tunnels in blue. District & Circle Line at higher level in brown. New works in grey

here without closing down the line. So instead we're coming at it from the back, creating a robust frame to support the edges when we make the hole." TWBN will excavate a 5.5m wide by 2.5m deep heading and connect a steel lintel to the outside of the cast iron tunnel lining. The heading will then be deepened incrementally allowing jambs to be attached in a number of short sections. Finally a sill will complete the bottom of the frame. The frame will be braced back and supported off the locally thickened sprayed concrete primary lining of the adit.

Ticket halls under major roads

Ticket hall boxes will be 15m deep. "Because we're excavating right next to old masonry buildings with shallow foundations, limiting ground movement is vitally important," says Mott MacDonald project manager Rob Dickson. Structural stiffness is being provided by large 1.2m diameter secant pile walls and the propping action of the boxes' roof slabs. Both ticket halls will be under busy thoroughfares – the North hall under Bressenden Place and South partially under Wilton Road. To minimise traffic disruption they will be built using top-down construction. The north ticket hall roof slab will be formed one half at a time, with traffic diverted from side to side to maintain flow.

Pursuing efficiency and safety

TWBN and LU are employing lean process and product efficiency principles on the project. Every activity is subject to planning and review, with the aim of eliminating waste. A major lean win has already been achieved on the jet grouting preparatory works. "We have 2,500 guide sleeves to install in advance of drilling," Lloyd says. "Our operatives told us that the sleeves we were using at the project outset were difficult to trim to length, so we experimented with a number of other materials and designs to find sleeves that were easy to handle and cut.

If you're saving even a few minutes per sleeve, the time saving to the project overall is considerable."

Improvements in materials and working methods made on this project are being shared across LU's portfolio of station capacity enhancement projects, Keelan reports. TWBN is employing a behavioural approach to safety that it calls 'Beyond Zero'. This involves all members of the construction team playing a part in drafting safe methods of working – termed SMOWs. Everybody is required to consider risks and how to eliminate them, with an eye not just on their own safety but that of their colleagues too. SMOWs are supplemented with daily activity briefings. LU completed site acquisition in March 2011, with site preparation beginning last summer. SCL tunnelling will start from shaft 29 adjacent to the North ticket hall and advance southward. Keelan says, "It is essential we protect the network around Victoria Station this summer – there'll be even more users than usual due to the 2012 Olympics."

The north ticket hall is scheduled for completion at the end of 2016. Work on the south ticket hall will begin in late 2012, after the Olympics. Victoria Station Upgrade is on schedule to be delivered into service in 2018.

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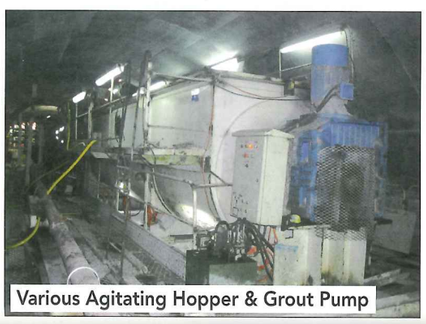
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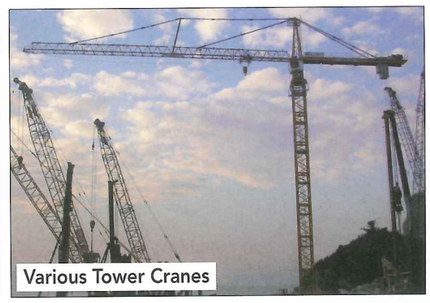
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Primary risk reduction

It is notable that many treatises on the subject of project risk management do not pay much attention to the subject of site investigation (SI), even though the gathering of accurate information before a tunnelling project commences is bound to decrease risk to a project. Today there is a wide array of techniques available to collect such information and costs that can be balanced favourably against overall project expenditure. Maurice Jones reviews some of these

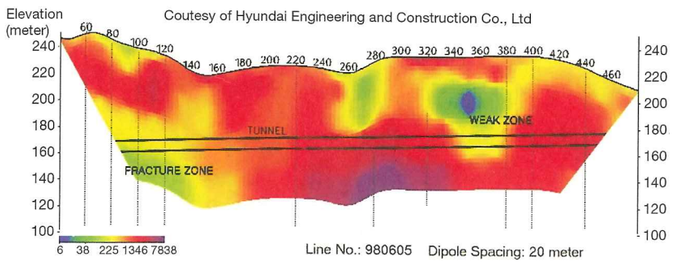
Average expenditure on site investigation (SI) for underground construction it has been reported has reduced to around one per cent of project costs, whereas the expenditure on site instrumentation and monitoring for a project in progress, particular in urban areas, has increased. This obviously reflects concerns about the consequences of third-party damage cause by settlement, but appropriate investment in information collection before final project plans are made will reduce project risk, including that of third party damage. In any case, some degree of site investigation will be needed to select appropriate sites for monitoring instrumentation.

The main difficulty is drawing the line on how much information is necessary, and how much it will cost. Obviously a tunnelling project, even in a high-risk area such as the centre of a city, is not likely to be able to budget for the level of exploration expenditure made in the oil and gas industry, and some mining projects.

Quiet apart from the general desire to minimise general risk, some of the specific reasons for SI are:

- The characterisation of rock to be excavated so that the best method, or methods, can be selected;
- The materials and structure of the ground bordering the excavation so that the best means of primary and permanent support can then be selected and designed;
- Coupled with the above, the development of a geotechnical baseline report that can be used as a reference for informing potential contractors, and aiding design;
- An assessment of likely and acceptable degrees of settlement, including interaction with any adjacent sensitive structures in the 'zone of influence';
- The avoidance of 'nasty surprises', of whatever type, that may be hazardous or otherwise delay project progress. These could include:

a) Major changes in geology, including boulders in glacial deposits and buried fault zones that may cause of change in tunnelling method or access points;
b) Cavities such as abandoned tunnels, karstic structures, and other solution structures;
c) 'Hidden' water courses, especially artesian aquifers;
d) Buried steel, such as piles, abandoned pipes or debris in 'fill', that cannot be easily excavated;
e) Unexploded ordinance from warfare;
f) Other hazardous materials, whether naturally occurring or from old industrial processes, such as methane, oil, fibrous minerals, other carcinogenic substances, arsenic, and acid water;
g) Unexpectedly deep foundation structures, especially wooden piles that may affect the stability of surface structures even if they can be cut through. These could also include items of archaeological significance.



Left: **Figure 1, plot of resistivity results on the alignment of a highway tunnel through weak ground in South Korea (Illustration: AGI & Hyundai)**

Methods

For their part, exponents of site investigation have adopted new technologies aimed at minimising the time and cost involved in site investigation, as well as improving accuracy. For many observers site investigation means boreholes and their sampling and instrumentation, as described in the next article, but there are many approaches that can gain valuable information.

Before investing in an active site investigation programme, it will probably be worthwhile to investigate what existing information is available on the ground conditions, structures and other data likely to be pertinent. This may include data from previous tunnelling or mining, boreholes undertaken for national geological investigations, mineral prospecting or water, oil and gas wells. The amount of data available will vary greatly from one region to another.

Even where there is substantial information available it may well be that there are major gaps in the knowledge that can indentify the main targets of a physical SI programme.

Specialist contractors usually have a wide range of geophysical methods available for site investigation. Many of these are based on identifying changes in density (including voids) or moisture that can reveal structural and material differences. According to Fugro Aperio, a specialist in engineering geophysics and other non-destructive structural testing techniques who claims to have probably the world's biggest team of engineering geophysicists, survey techniques include:

- Ground penetrating radar (GPR),
- Ground resistivity/ERT,
- Ground conductivity,
- Magnetometry,
- Seismic methods including refraction and reflection,
- Multichannel analysis of surface waves (MASW- seismic),
- Microgravity,
- Cone penetration testing (CPT) at the surface coupled with advance positioning methods and any required sampling. These methods can present both numerical data and charts or sections that, with specialist interpretation, can display anomalies.

Ground penetrating radar found its first applications in ice fields, locating shallow non-metallic utility lines, and even in crime-scene investigation to find suspected buried bodies. In recent years it has been developed rapidly to detect all forms of subsurface anomalies, objects and cavities. It has also been adapted to detect voids behind existing tunnel linings, and has even been tried in the heads of TBMs as advance warning of problems in advance of the face. Fugro Aperio secured a 3-year Royal Society award to support research into ground penetrating radar for civil engineering applications in conjunction with Keele University, Staffordshire, England.

Penetradar Corp of Niagara Falls, New York state, has developed a number of ground penetrating radar antennae including compact devices than can be used on suitable carriers for investigating the state of existing tunnel linings including lining deterioration, subsurface moisture and its location, debonded surface tiles and lining separations.

Resistivity surveys, which, like GPR, have found widespread application in archaeological investigations, are another popular method of investigating conditions below the surface, carried out by applying an electrical test current between two dipole electrodes. Developments in improved electronics including miniaturisation has led to much more portable instruments well suited to field work, even in remote locations.

As an example, Hyundai Engineering & Construction Co carried out site investigation for mountain tunnel construction for a motorway in South Korea using the Sting/Swift automatic resistivity imaging system from AGI (Advanced Geosciences, In) of Austin, US. As can be seen from the accompanying illustration of one of the survey lines, a longitudinal section along the 2km highway tunnel alignment was covered using 27 electrodes at 20-m spacing for a total length of 520m. The dipole-dipole electrode array was used, and the recorded data of apparent resistivity was converted to 'true' resistivity, with corrections for topography, using the DIPRO software developed by Dr Kim of the Korean Institute of Geology, Mining & Minerals. High resistivity zones, shown in red (Figure 1, opposite), indicate solid rock, whereas low resistive areas (yellow, green and blue) indicate fractured zones with water, making the zone more conductive.

Above: **A cone penetration test (CPT) truck from Fugro Geotechnical Services**

Left: **A ground penetrating radar instrument used for detecting buried services, objects, etc in a highway (Photo: European GPR Assoc)**

Several zones of low resistivity could be identified. During construction progress stopped at 380-350m at the weak zone for probe drilling at the face to better locate the weak zone, which was confirmed at 350-340m. The resistivity indicated fracture zone at 80-140m corresponds to the findings of a geological survey.

As outlined in the next article, several investigative methods have been developed into modules suitable for borehole use. In addition to obtaining quality samples from its boreholes, both onshore and offshore, for the Lake Mead Intake Number Three project, Crux Subsurface carried out additional surveys through its Crux Oriented Borehole Logging (COBL) service. In situ testing included optical and acoustical televiewer surveys, natural gamma radiation detection, a temperature profile, permeability testing and dilatometer testing. Crux was working with MWH and CH2M-Hill for the Southern Nevada Water Authority.

The importance of detecting historic sites in advance of proposed tunnel routes is illustrated by the case of the Bosporus crossings. As part of the Istanbul Strait Highway Transit Project, the ATAS Company has prepared a plan to preserve historical artefacts on the European side from the Cankrtaran shoreline to Haydarpasa. This is to avoid the delay of about 3.5 years to the previous Marmaray Project. GPR was used to scan the tunnel route to detect historical remnants. This and other geophysical methods have been used especially at underpasses and cut-and-cover sections.

Pilot

In some circumstances tunnelling project promoters go to the opposite extreme in site investigation by driving a pilot bore on the alignment. This is not likely to be an economic option unless the bore were, in some way, to form part of the ultimate structure, such as by enlargement or perhaps by forming a service or access tunnel. The major advantage is that a pilot bore can demonstrate the behaviour of excavated ground on a more lifelike scale. There could also be a political element to the decision to make a pilot bore such as to create a near *fait accomplis*, or to demonstrate progress in full construction when the promoters are still being cautious or do not have full funding available.

It is likely that a pilot bore would still be preceded by a more conventional site investigation programme such as to check for structural anomalies that could make a pilot bore a waste of time if it were planned for a poor alignment.

Project monitoring

Although not strictly site investigation, the process of monitoring for any movements which may be a result of underground construction activity has important links with original site investigation and its findings. The information found during site investigation, especially related to the location and condition of existing structures, and any other major features such as caves and waterways, may have an important bearing on planning the instrumentation stations for monitoring.

As part of the upgrading of Victoria Underground metro station in London, Itmsoil installed, commissioned and managed a range of instrumentation including five Leica TM30 total stations to monitor movement of buildings within the predicted zone of influence.

As part of its R&D programme Itmsoil has been developing special low-profile reference prism reflectors used as surveying targets. Of particular relevance to Victoria is a miniature version that is deployed on several listed and other 'sensitive' buildings such as two theatres, the major surface railway terminus and office blocks. Whilst functioning perfectly for surveying purposes they are difficult for the casual observer to note on the buildings, and so do not detract from the aesthetic values of the listed structures. Eight reference prisms are laced outside of the 'zone of influence' of the works. In addition to the five total stations on the surface itmsoil has deployed 13 more Leica TM30 total stations underground.

As an indication of the huge investment likely to be required for the monitoring of major underground projects now, on its Crossrail monitoring contract, Itmsoil is installing 300 motorised theodolites associated with many times more reference prisms throughout the scheme.

Within the Soletanche Bachy group, SolData conducts chiefly instrumentation and monitoring activities. Geophysical surveys are mainly the activity of sister company EDG (Europeene de Geophysique). Since 1 January it has become part of SolData and renamed SolData Geophysic. It has a staff of 30 specialists conducting seismic, electrical resistivity and radar tomography surveys amongst other services.

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This Sandvik DE710 diamond core drill operated by E-Drill in Australia is one of the large DE range for maximum hole depths from 230 to 3174m

Getting to the core of the matter

Since there still seems to be a marked reluctance in many quarters to spend much on site investigative work before main tunnel construction commences, it is fortunate that drilling, probing, sampling and testing methods are gradually becoming more efficient in terms of speed, accuracy and, hopefully, cost. However this demands a much higher level of sophistication in the technology employed. Maurice Jones checks on what is available

Where there are gaps in site knowledge it is likely that some form of physical investigations will be undertaken, whether to fill these gaps or to investigate a virgin area. While there any many possible means of site investigation, as outlined in the previous article, boring a hole and testing the properties of the surrounding ground and/or any samples extracted, is still the usual and arguably the most informative approach.

Drilling information

To the uninitiated, drilling a hole to find out what lies beneath may seem a simple matter once the location of the head of the bore is know, but there are many factors affecting the accuracy and relevance of data that can be obtained by this apparently simple act. The choice of equipment will be greatly affected by factors such as:

- Location of the borehole (determined accurately by surveying or GPS) and the terrain there,
- Depth from which information required,
- Type of ground likely to be encountered e.g. hard, soft, abrasive, fractured, waterlogged,
- Physical property data required,
- Accuracy required including hole orientation,
- Whether a permanent sample is required (e.g. a core) for lab testing or records, and from which horizon(s),
- Speed information required

Location

If the required drilling location is on relatively flat, accessible terrain, it should be no problem using a high-capacity, powerful rig, perhaps truck-mounted for mobility. If a mud drilling system is required this will reduce mobility to allow for the additional mud treatment system etc.

On rougher terrain a drill rig with a crawler carrier will be necessary. Even so the capacity and other capabilities of the rig will be roughly proportionate to the size of the rig, which, in turn, will affect its ability to access the desirable drilling site on rough terrain and remote locations.

Sometimes information will be required from beneath a stretch of water, typically for planned tunnelled crossings of a river or other waterway, or for special major structures such as the planned Thames Water's Thames Tunnel in London. If there is room on the waterway, taking into consideration such factors as required navigability, a barge with jack-up legs can be used to house, transport and act a platform from which vertical or near-vertical drilling can take place. If the water is not accessible, then the strata from which information is required will have to be reached from a 'dry' location. This can be achieved by an inclined hole from the surface, a horizontal bore from an underground or open-cut excavation, or by directional drilling (see below). In all cases it follows that borehole surveying, whether post-drilling or by measurement while drilling (MWD), will need to be accurate to determine the correct location and orientation of the borehole, and hence the information being sourced.

Rigs

There are many different types of drill rigs suitable for some form of site investigation, with associated borehole equipment too numerous to mention all here. Prime movers can be from (on the surface) internal combustion engines with mechanical, hydraulic, electric or compressed air drives, and usually electric supply to hydraulic or air drives underground.

Most modern site investigation drilling operations will use lengths of metal or plastics drill pipe connected together to form the drill string, but much slower traditional cable drilling may be used for shallow holes or where the labour costs are low and there is little urgency. Casing will be used to support unstable bore walls.

Most modern, accurate site investigation rigs will have a rotary drive, either top-drive or a table Kelly drive, but non-rotary direct-push rigs and vibratory 'sonic' systems have limited applications.

Trends in the design of modern site investigation rigs have generally kept up with trends in all, chiefly surface, rigs for more efficient, environmentally acceptable drives, better safety as regards operator protection, and the prevention of excessive load handling by the introduction of mechanical drill-pipe handling devices etc.

Erik Mattsson, product line manager for Mustang geotechnical rigs at Atlas Copco comments that a rig's chief function is as a tool-holder only, but one that must be capable of providing the right drilling data through accurate control of speed (rev/min) and proper drill string support to hold back

Below: **Diamond coring bits used in the Atlas Copco Geobor S multi-function system**

the weight on the bit for accurate coring. Versatile rigs will be expected to be capable of auger-boring as well, in which case provision of the correct torque from the drill head will more important than speed.

"Very important in site investigation is easy set-up and transportation', says Mattsson. This enables the drill carrier to visit a number of widely spaced sites, perhaps under difficult surface conditions, rather than the case with blast hole drill rigs that tend to operate in one area for longer periods.

"Another important rig design trend is ergonomics for a good drilling position", Mattsson points out. "The operator needs to have a great view of operations, but not too close to moving parts. Having the controls on an adjustable arm helps this, to give a suitable distance between the operator and the rig itself. Remote control systems are getting more popular but not yet for tramming. Normally a rig should be easy to use in awkward places, but we find that drilling location access problems are not a major issue with users. In fact we have several requests for truck-mounted rigs. Oscillating crawler carriers for rough terrain also make the rigs heavier for transportation or steep slopes."

Atlas Copco Mustang geotechnical rigs for site investigation are generally supplied on comparatively light crawler carriers for operation on rough terrain with rapid tramming and ease of transport between sites. The manufacturer's Diamec rigs dedicated to coring with diamond or tungsten carbide coring bits are in smaller units, facilitating their use underground, chiefly in the mining industry, and so lending themselves to portability. Atlas Copco also supplies larger reverse circulation rigs for deeper bores with sampling of the drill chippings.

A rig capability for using the overburden drilling with eccentric bit (ODEX) method, or similar, for drilling below a casing in unconsolidated ground should aid the penetration of loose overburden preventing its collapse into the hole, and also preventing contamination of any sampling.

Coring

In many ways the key to high quality site investigation through drilling lies with what happens in the borehole in the correct position that is of interest. To achieve the maximum site investigation efficiency the equipment must be capable of testing as many physical properties as possible within the holes coupled with accurate indexing of hole orientation so that, where necessary, the results can be presented on the correct orientation. For tunnelling this may be particularly important to access jointing and fractures that may affect suitability for mechanical cutting in tunnel excavation, or the necessary support characteristics.

Versatility in testing for ground properties in the hole also minimises the need for time-consuming removal of the whole drill-string.

Coring tends to have limited use in site investigation (as distinct from mining sampling) due to the additional expense, but it does provide a physical sample that can be subjected to more accurate testing in a lab, and provide a physical record if required. The same criteria of accurate recording of the coring horizon and orientation apply as far in-hole testing. Unless the ground consists of competent rock with few fractures, special equipment may be required to recover a useful core in soft or incompetent ground.

Peter Hedenstedt, product line manager for Terracore products at Atlas Copco explains, "There is a bit variation in the type and material of site investigation bits depending on the expected rock type including those made of tungsten carbide, diamond, and polycrystalline diamond (PCD). But what you want is undisturbed core sampling, with the material as close as possible to the conditions of its natural environment. The trouble is a core is usually disturbed as soon as it starts to be hoisted to the surface, especially in unconsolidated ground. The wireline system with core catcher was developed to allow cores to be recovered without moving the drill string tubes, which would otherwise causing further disturbance and delay. The drill rods and the outer tube thus serve as casing and remain in the hole during round trips."

There have been a number of developments since wireline was first introduced, all aimed at improving the quality and performance of core recovery. There have and continue to be efforts aimed at increasing the versatility of equipment used. One of these is the Terracore Geobor S system that can be used in seven different modes of operation (representing different testing and sampling techniques), and another soon for release. The system can be used in a wide range of ground types with various rotary drill rigs

Left: One of Atlas Copco's Mustang geotechnical rigs, the 4-F4 can be used for wireline core drilling and Standard Penetration Test (SPT) operations with the Geobor S system

provided the torque capacity is sufficient for the type of rock formation and the required hole depth, available pull down force is 4-5t, pullback force 6-8tf, and available rotary speed 25-300 rev/min. The rig must also have a wireline hoist and suitable flush pump. Core barrels are available in lengths of 1500mm and 3000mm.

The Geobor S employs are larger than usual core barrel (146 - 150mm hole diameter) that can accommodate a 4-inch (102-mm) diameter core. Using a triple-tube core barrel in the Geobor S, the inner tube has a liner to hold the core, and with the wireline just attached to the liner. Glands are often installed at each end of the liner to hold in any moisture, and the wireline used to recover the core-holding liner. In unconsolidated ground this achieves the aim of core recovery as near as possible to its natural composition and with minimal or no disturbance. Sampling can be carried out throughout the horizontal 360 deg. If underground drilling requires inclined holes, the inner tube/sampler can be pumped into the hole with the flush pump.

The bottom of the Geobor S core barrel can be equipped with different tools (forming the seven to eight different methods of operation), selected according to the formations to be penetrated. "One method," says Hedenstedt, "is to obtain a sample by punching a hole in soft enough ground, but this is considered rather old fashioned now, with more sophisticated and accurate methods being available such as the Devico methods and those of Reflex Drilling in Australia."

The Geobor S system has been used extensively, by various site investigation contractors, in the construction of the German DB high-speed railway network with its numerous tunnels. Drilling depths have been typically around 120m, but down to 200m maxima. There have also be some horizontal holes of up to 130m length. Tectonic movements have damaged the sedimentary ground with some basalt layers in several locations.

Although not site investigation for tunnelling, Fugro Seacore employed its 8-leg jack-up platform for investigations in the Irish Sea for proposed salt-dome gas storage caverns. The contractor used an oversize (197mm diameter) Geobor S bit inside a 9 5/8-in. casing to produce 660m of core with a 97 per cent core recovery rate.

The smaller rigs that may be associated with TBM probe drilling processes, or for some other underground duties, tend to have smaller coring equipment of around 60mm diameter.

Above: Atlas Copco' s Diamec U6 underground core drilling rig that can be easily positioned for any direction

Where?

A development of coring systems developed by Viktor Tokle of Norway is the Devico directional coring system.

The principles of directional drilling were originally developed in the oil and gas industry, chiefly for exploiting fields across a wide area from one location, or to access reserves where vertical drilling would be problematical.

It has now been developed in to a range of applications including site investigation, but necessitating a very accurate method of hole position monitoring, which is available with the use of Devico borehole surveying instruments.

The system offers multiple 'sidetracks' for investigating in different directions and depths, with full control of deviation. Less set-up positions reduce exploration time and costs, and reduce environmental impact.

Testing

Apart from coring and other sampling techniques, modern in-bore instrumentation systems owe much to developments for the oil and gas industry.

While this industry can more readily afford to investment in such sophisticated technologies, some filter through to tunnelling projects, especially when they are on a grand scale.

One of the leading developers in this context is Schlumberger which, incidentally, has just purchased the Smith drill tool company. Its latest introduction is MicroScope 475 that provides 'key' information for formation evaluation and fracture identification. It represents a high-resolution resistivity and imaging-while drilling service for logging data.

Probing ahead

Once tunnelling has commenced, whether the main project excavation or in the form of a pilot bore, it may be found that the ground conditions are not what was previously expected. This may be due to a previously undiscovered fault zone or fissure allowing water into the excavation.

In such cases probe drilling ahead of the tunnel face may be required. To some extent probe drilling can be carried out by conventional blast-hole drilling rigs, using the performance indicators available on modern rigs to assess the ground conditions ahead. Similarly, with TBM drives, the TBM itself may carry small probe drills to investigate the ground ahead.

For more extensive investigations at greater hole lengths the normal excavation equipment will have to be withdrawn and a specialist rig installed, this will give the additional facilities of coring and longer holes, probably with larger diameters.

In some cases such additional site investigation may be accompanied by grouting operations to consolidate any poor ground found in advance of the tunnel.

Rock cavern design on the West Island Line

In 2011 two new underground stations on the West Island Line were under construction beneath dense urban areas. Only one MTR station rock cavern, Taikoo, had been constructed before, and in a much less challenging area. This paper by Eric Chui and Paul Lee of Atkins China, and Robert Mackean of Geo-Design Consulting Engineers, presents in outline the design concepts for Sai Ying Pun and Hong Kong University station caverns with site constraints, ground conditions and concept selection

The West Island Line (WIL) will extend the Mass Transit Railway Corporation (MTRC) Island Line (ISL) from the existing Sheung Wan Station to the western district of Hong Kong Island, and add approximately 3.3km of underground route to the existing Line. Three new underground stations, Sai Ying Pun Station, Hong Kong University Station and Kennedy Town Station, will be built along the line. Kennedy Town will be a cut and cover station, and Sai Ying Pun and Hong Kong University will be deep cavern stations. Figure 1 (far right) shows the underground view of the WIL.

Selection of a cavern option was primarily on account of the lack of available land in the densely populated areas of the western district. The alignment was conceived following evaluation of a number of alternatives taking into account the physical constraints (for example existing buildings and their foundations), the need to connect the three new stations to the ISL west of Sheung Wan Station and the need to locate the caverns within a competent rock mass. The depth of the proposed cavern stations vary between 50 and 80m below ground level.

The two WIL caverns will be the first station caverns built by MTRC for over 25 years and will be the first caverns of these spans to be built beneath Hong Kong's densely urbanised areas. There was little local precedent to guide development of the design concepts, which also had to be developed under close scrutiny from Buildings Department and the Geotechnical Engineering Office. Experience with cavern engineering from overseas was combined with knowledge of local practice and design standards to produce an approved reference design.

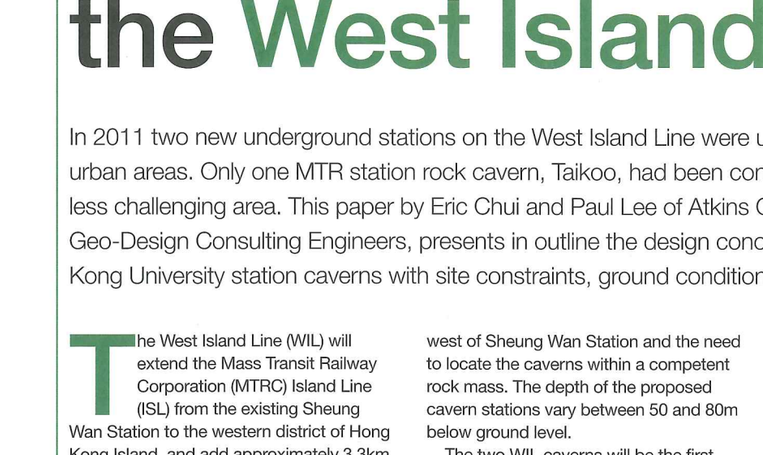
Site condition and structural geology

The proposed Sai Ying Pun Station cavern is located beneath the colluvium-covered sloping ground at the foot of Victoria Peak, beneath the Centre Street and High Street area. More than 30 buildings constructed on various types of foundation, such as friction piles, end-bearing piles and pad footings, are located above the footprint of the cavern. The station is orientated in a southwest–northeast direction with the ground level dipping steeply towards the north from over 50m above Principle Datum (mPD) in the southwest to less than 30mPD in the northeast.

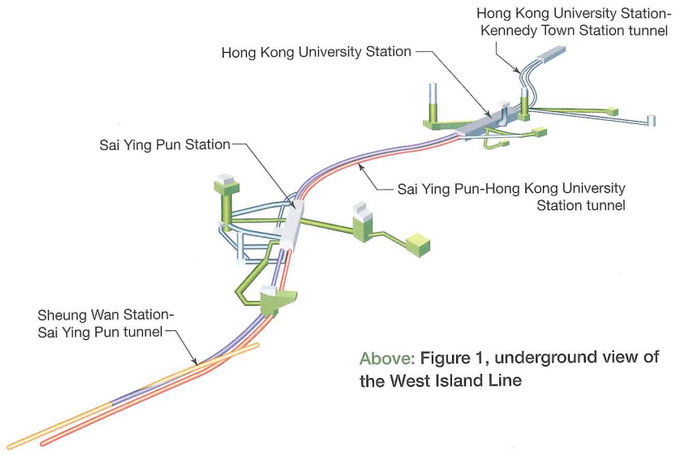
The proposed Hong Kong University Station cavern is located in an area of sloping ground to the north of Lung Fu Shan, beneath Pokfulam Road, with a number of existing buildings around the area. The cavern is orientated in an east-west direction, and ground levels decrease from +80mPD at the western end to less than +40mPD at the eastern end.

The published geological maps of the region indicate the overall trends of faults with northeast-southwest and northwest–southeast orientation. Hong Kong University Station has an east-west orientation and is therefore intermediate to each of the trends, while Sai Ying Pun Station is sub-parallel to the dominant northeast-southwest trend. No major faults are shown in the vicinity of Sai Ying Pun Station and a single fault with a northweast-southwest orientation is shown just to the south of Hong Kong University Station, which if extrapolated towards the northeast intersects the eastern end of the cavern. A number of other lineaments, representing possible geological structures had been identified by studies of the topography and aerial photographs (MTRC, 2008a).

Both vertical and inclined boreholes were planned to investigate the rock mass conditions. The aim of the inclined holes was to provide data on the subvertical structures, including major structures and faults which could impact on the stability of the cavern excavation. However, due to access difficulties and the presence of existing buried utilities, complete coverage of the cavern areas was not possible. The evidence for most of the inferred geological features was limited. However, one of the inferred features predicted to intersect the eastern end of the Sai Ying Pun Station cavern and platform tunnels was encountered in several boreholes. This adverse geological feature was characterised by closely spaced structure and altered material some 0.7m thick. The eastern end of the Sai Ying Pun Station cavern thus comprises a shallow rock cover of partially weathered rock mass intersected by an altered adverse geological feature. In order to investigate this feature further and to provide an opportunity for detailed characterisation, and also if necessary to undertake treatment, an advanced pilot tunnel, from the construction shaft at King George V Memorial Park was recommended. The pilot tunnel will form a part of the permanent works for access.



Left: Interior view of WIL cavern



Above: **Figure 1, underground view of the West Island Line**

Cavern layout

The Sai Ying Pun Station is 225m long and comprises a 187m long cavern and a 38m long platform tunnel extending from the northeastern end. The cavern is located approximately 40 to 65m below ground. It has an excavation span of 22.8m and a height of 16m, and will be built with a moderate rock cover of 50m at the western end and a rock cover of only 10m at the eastern end. In view of the shallow rock cover at the eastern end of the cavern construction, two-finger platform tunnels with a reduced size of approximately 9.5m in width and 10m in height have been proposed. The platform tunnels will be separated from one another by a 3m wide rock pillar.

The Hong Kong University Station comprises a 240m long cavern with an excavation span of 22.4m and a height of 16m. The overall depth of the cavern is similar to that of Sai Ying Pun Station and varies between 48 and 80m below ground level. However, the rock cover is greater and is anticipated to be around 65m at the western end and 25m at the eastern end of the cavern.

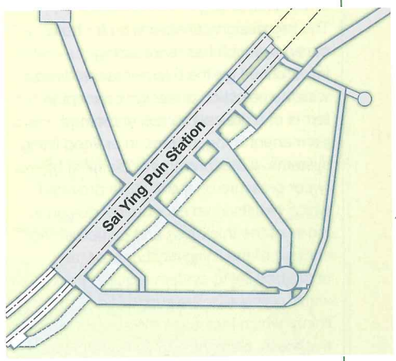
The orientations of the caverns were governed by the existing Sheung Wan Station and its overrun tunnels, allowable turning radius of the railway line, physical constraints of existing structures and their foundations, and the location and depth of competent rock. A further review of the geological data at the detailed design stage concluded that shifting the position of the Sai Ying Pun Station cavern 50m towards the west would increase the rock cover significantly and hence reduce the risks associated with cavern construction. However, because of the railway operational constraints on cant and curvature, as stipulated in the MTR Design Standard Manual on railway engineering design, the station was shifted 18m to the west.

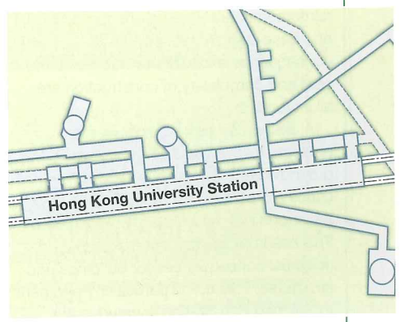
The various rock pillars associated with each cavern were designed taking into account the anticipated quality of the rock mass, joint orientations, and the width and height of the adjacent cavern and adits. Stress concentration and distribution at each construction stage were estimated. The derived layouts have a pillar width typically a half to two-thirds of the tunnel cavern height (GEO, 1992).

Cavern design concepts

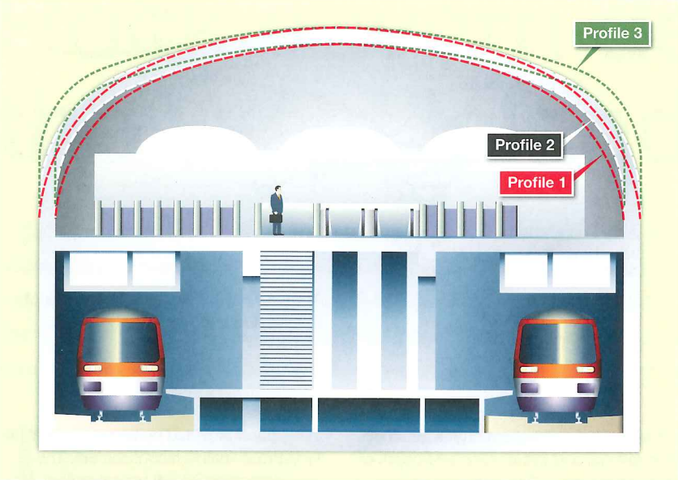
Excavation sequence and support

The cavern will be excavated using drill and blast methods with temporary support to enhance the intrinsic stability state in order to provide adequate stability reserve at all stages of construction. Temporary support will comprise rock reinforcement and shotcrete installed in the crown and sidewalls incrementally as the excavation proceeds. The supports will also be installed within a specified distance from the excavation face in order to benefit from the support provided by the excavation face and to maintain confinement. The maximum advance will be varied according to the ground conditions and proximity of adjacent openings. Rock bolts and shotcrete, which can be installed quickly and easily, were adopted in the reference design. Preliminary excavation sequences of the caverns themselves together with those of their adjacent adits were developed in the design. Development considered the benefits of various sequences in terms of rock engineering and





Right, above: **Figure 2, general layout plan of Sai Ying Pun Station;** Right: **Figure 3, same of Hong Kong University**



Above: **Figure 4, sensitivity check on cavern shape**

maintaining stability, access from side adits to the main opening and considered construction issues including typical plant size for the installation of rock bolts with reference to the height of the top heading.

Selection of drained versus undrained lining

The key design consideration for both caverns, which has far reaching implications for the overall cavern design was the selection of design concept in terms of a drained versus undrained permanent lining system. In drained lining systems, a mechanism for the relief of water pressure on the lining is provided which results in an economical design in terms of the thickness and reinforcement content of the lining. By contrast, an undrained lining system requires the full water pressure to be supported by the lining, which increases the structural thickness. Straight side walls become difficult to engineer due to the quantity of reinforcement required and a curved invert and base slab are required. As a consequence excavation volume and the cost and complexity of construction are all increased.

A drained system is permanently pressure relieved and allows flow of groundwater into the cavern, which could cause a drawdown of groundwater levels in the superficial materials in the long term. This has implications for settlement and potential consequences for buildings and structures. This risk is particularly pertinent to Sai Ying Pun Station, located in the centre of Sai Ying Pun where many old buildings are built on a variety of foundation types including settlement sensitive friction piles.

A hydrogeological assessment was undertaken to study the potential impacts of drained caverns and to examine the influence of depressurisation on the hydrogeological regime. The results suggested that a drained cavern concept would be feasible for both Hong Kong University Station and Sai Ying Pun Station. A drained system was therefore designed and accompanied by specifications for groundwater control during construction, including for probe holes and water inflow criteria to govern pre-excavation grouting requirements; a comprehensive instrumentation and monitoring scheme; and a grouting design at critical locations.

To reduce the risk of groundwater pressure build up on the lining with time, the design includes the installation of a highly conductive geotextile behind the lining to facilitate inflow of water from the surrounding rock mass to a drainage invert of 300mm thick rock fill. Collected water will be diverted to a sump via drainage pipes located along the cavern invert.

Rock mass classification

The Q-classification system is often adopted as a basis for tunnel design in Hong Kong and it is straightforward to apply in terms of design and implementation. As is well known, Q - support correlations are based on the assessment of case studies covering a wide range of rock mass conditions (Barton, 1998). However, for wide span caverns in weathered rock, perhaps influenced by particular discrete structure or for those with a small amount of rock cover, the precedent data is limited. The predictive reliability of Q-based support estimation for such conditions is therefore also limited.

A project-specific rock mass classification system was adopted to provide a framework for core characterisation and for developing deterministic geological and rock mass models representative of the range of probable ground conditions for each cavern. The classification is summarised in Table 1 (MTRC, 2008b) (Bandis, 1997).

A key attribute of the Hong Kong granite is the weathering state of the sub-horizontal structure, which can form weak persistent structures and thus be very influential on stability of large spans (Sharp, J.C, 1989). The rock mass zonation subdivides the cavern area into rock masses with similar attributes in terms of weathering characteristics, particularly the weathering state of the subhorizontal structure. Four zones were identified ranging from Zone A, which mainly contained Grade I and II rock with unweathered sub-horizontal joints, to Zone D, which mainly contained Grade III rock with highly to completely weathered sub-horizontal joints.

Superimposed on and cutting through the weathering zones are a variety of subvertical structure types. From a review of the published geology and the inspection of cores, five principal types can be identified ranging from SV1 comprising widely spaced joints with no infill, to SV4 and SV5 which represent discrete zones of alteration and geological faults.

This rock mass classification system was provisional at the time of the detailed design stage and will be reviewed and updated as data becomes available during the construction process.

Cavern shape

Once drained caverns had been selected as the preferred option the cavern shape could be developed.

Selection of cavern geometry was driven largely by the aim of maximising the intrinsic stability of the excavation, so as to decrease temporary support requirements and reduce construction risk. Persistent weathered sub-horizontal joints have been identified as having a key influence on crown stability when present. A flatter arch profile was evaluated as a method of reducing the extent of intrinsically unstable haunch areas and minimising potential overbreak. Adoption of vertical sidewalls allows a relatively rapid excavation using vertically drilled bench blasting and simplifies formwork for casting the final lining. The combination of vertical walls and a flat arch roof offer more functional space.

Design of temporary supports

Rock mass models developed by applying the classification system described above were used directly as a basis for distinct element models. The models represented, as faithfully as possible, the distribution of structure types as actually encountered in the borehole core. The force-displacement behaviour of the discontinuities was modelled using the Barton Bandis failure criteria, applied to each discontinuity type based on their physical attributes [Bandis et al, 2011] [Barton & Bandis, 1987] [Barton & Bandis, 1990] The derived constitutive model is non-linear and stress strain dependent.

Modelling using the Universal Distinct Element Code (UDEC) was undertaken to assess the intrinsic stability at each stage of the proposed excavation sequence. The influence of model attributes were studied, including the sensitivity of the rock mass response to strength of particular structure, water pressures and in situ stress. Based on the observed rock mass behaviour, the modes of failure and the extent of overbreak, rock reinforcement layouts were designed and the models re-run with the support installed incrementally with each stage of excavation. Adequate stability reserve was demonstrated at each stage of the cavern cross section development and the loads induced in the rock reinforcement used to design and specify the units.

It is recognised that the outcome of a UDEC model is entirely dependent on the validity of the geological model and related assumptions. These assumptions need to be verified on site based on detailed deterministic records of the geological structure encountered, using the project geological structure classification or similar. From the authors' experience, for the design implementation and verification process for major cavern developments it is not adequate to rely solely on records of Q values of the encountered conditions as the influence of major structure, which can dictate the behaviour of the excavation, become unduly attenuated, and their significance lost.

The management of the design implementation and verification process is one of the key risk mitigation tasks for successful cavern engineering. It should be recognised however that the required resources, methods and standards of data presentation are different to those adopted on long, smaller span, tunnel alignments in HK and elsewhere.

Permanent cavern support - concept

A cast in-situ locally reinforced concrete lining was the preferred permanent support option and was adopted for both caverns. The principal benefit was to enable a water proof membrane to be placed in order to achieve the high standards of water proofing required for an MTRC station (MTRC, 1997). The lining was also designed to support the concourse base slab. A secondary benefit was installation of the overhead electrical and mechanical (E&M) system which would be more difficult with a permanent shotcrete lining. The concrete linings have been designed for long term durability with the aim of minimal maintenance costs.

The performance of the final lining in terms of structural efficiency is sensitive to the shape of the cavern, and is also influenced by the geometry of intersecting adits. Three cavern arch profiles ranging from a relatively circular profile, to an elliptical arch and a flat arch were studied to optimise lining design, and are illustrated in Figure 4.

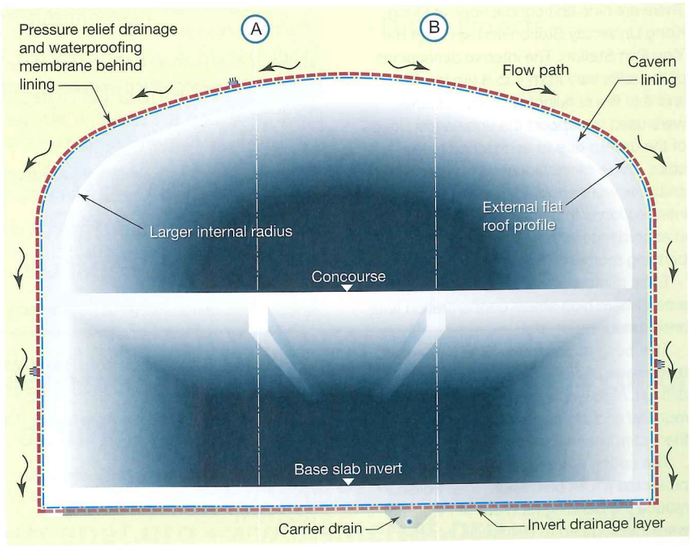
Sensitivity analyses showed that the haunch zones are prone to build-up of bending moments, particularly in the case of haunches with small radius.

All adits that connect to the cavern will have internal finished levels coincident with that of the concourse slab. High horse-shoe adit openings were essential to provide sufficient space to house ventilation ducts and E&M equipment. As a consequence, the crown of the adits will intersect the main cavern at the haunches rather than within the vertical sidewalls. Two alternatives were considered as follows:

- Increase the height of the cavern such that the adits intersect with the straight sidewall of the cavern to form a simple interface. This reduces bending moments in both adits and the cavern lining but increases the excavation volume;
- Maintain the height of the cavern and let the top of the adit intersect with the cavern haunches. This has the advantage of optimising the excavation volume but increases the complexity of interface and design of the reinforced concrete collar.

By examining different models, a geometry was developed which maintained the optimised external excavation profile and an internal profile with a larger radius. This arrangement allows for an efficient final lining and improves the collar geometry.

To minimise the number of different shutters required to form the cast in-situ concrete lining the cavern crowns, Sai Ying Pun Station and Hong Kong University Station adopt the same profile, except for a 400mm flat section at Sai Ying Pun Station that has been provided in the centre point to accommodate the larger span.



Right: **Figure 5, general arrangement of lining and water pressure relief system**

Determination of rock loading

The rock loading for the permanent lining design was first estimated based on an empirical approach in accordance with 'Updating of the Q-system for NMT' (Grimstadt & Barton, 1993] and 'Engineering Classification of Rock Masses for the Design of Tunnel Support' (Barton et al, 1974).

The rock loads were also derived from the two-dimensional UDEC simulations. These loads are derived from the modelled interaction of the lining with the rock mass surround and provide loads representative of the actual rock mass behaviour and the stiffness of the lining as constructed.

Cast in-situ concrete lining was adopted for the permanent support of the caverns. The linings were designed by elastic analysis using the rock loading obtained from the UDEC model until effective stress conditions. A waterproofing membrane was provided behind the final lining to meet the requirements of water tightness. The main components are as follows:

- Target radial drainage holes drilled through the shotcrete lining and into the surrounding rock;
- Perforated, circumferential PVC drainage pipes (or geodrains) at 5m centres along the station, strapped and shotnailed to shotcrete substrate, and connected to invert drains;
- Protective and drainage geotextile held in place by shotnailed 'roundels';
- Waterproofing membrane with double-welded (overlap) joints.

There are nine adit connections at Hong Kong University Station and seven at Sai Ying Pun Station. The internal dimensions of the adits vary from 4 to 8.9m in width and 4 to 6m in height. Collar structures were used to support the unbalanced loads of the cavern due to connection to the adits. Three-dimensional numerical analyses were adopted to design the intersection with reinforcements allocated in accordance with the averaged strip of bending moment and shear forces.

Extra reinforcement was allocated in areas where high stress concentration was anticipated.

The fixing of concrete reinforcement at the crowns of a high and wide cavern is difficult, high working platforms are often required and increase the risk of damage to the waterproofing membrane.

The option of using double corrosion protected (DCP) permanent rock bolts to reduce the bending moment of the lining were investigated to determine whether lining reinforcement at the crown could be eliminated. The bolts were introduced into the UDEC models as part of the incremental excavation and support and then were retained in the long term after the lining was formed. From the analysis undertaken it was concluded that with the use of permanent rock reinforcement, an unreinforced cavern crown would be possible in sections of the cavern away from the adit intersections.

However, for the sections of the cavern with adit connections, crown reinforcement would still be required even with the use of DCP bolts. Over 60 per cent of the cavern length is influenced by adit connections.

In addition it was necessary to provide minimum reinforcement throughout the length of the cavern for fire proofing purposes and for these reasons reinforcement was adopted in the lining throughout instead of DCP bolts.

Discussion and conclusions

Hong Kong University Station and Sai Ying Pun Station illustrate that, with the right topography and geological conditions, railway stations formed within rock caverns can bring significant benefits. The cavern option for WIL allows Sai Ying Pun Station and Hong Kong University Station to be built in a congested urban area with minimum access required from the ground surface, minimising disruption to the public, and the release of more land for other uses.

Various key factors in the rock cavern design were discussed. The advantages of project-specific rock mass classification systems, which assist in development of distinct element models were outlined, and the benefits of a drained cavern structure described including the influence on cavern geometry. The design was largely based on information from surface boreholes and published geological data. The extent of this information is consistent with the complexity of the project however uncertainties exist in the models which will have to be developed during construction to facilitate design verification and validation. These stages are a vital component of risk mitigation on major rock engineering schemes.

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Safety and communications solutions for confined spaces

Designing an underground communications and safety monitoring network can be a daunting task for the less-experienced tunneller. Industry leader Mine Radio Systems gives some guidance on how it works

Given the importance of safety and communication solutions in rail tunnels, subway tunnels, service tunnels, utility tunnels and also tunnel construction projects, it's important to look for a supplier with a long track record and extensive experience in a wide range of tunnelling projects in locations all around the world.

It's also useful to insist on solutions that are customised to meet all your communications and safety needs while meeting or exceeding all necessary industry certifications and safety standards.

Here are some additional tips:

1. High-speed data connectivity

Implement a communications solution that provides high-speed internet services between surface and underground via leaky feeder cable technology. That means you will be able to use both VHF portable radios and voice over IP handsets. You should also make sure that your solution allows for 'hot spots' to be deployed strategically anywhere a leaky feeder cable is installed.

2. Precise and reliable airflow monitoring

Install airflow sensors that monitor the air flow through a complete drift cross section. This technology virtually eliminates the errors associated with turbulent flow near the sensor.

3. Exceed safety standards

Create extra layers of safety for operators by installing multi-level asset location and personnel warning technologies that are engineered specifically to exceed the standards for safety in the various tunnelling industries.

4. Collision prevention

Look for a system that not only provides a visual and/or audible alarm to notify the operator or personnel of impending danger, but also stores this information in a database, where it can be analysed by management.

5. Cost-effective and certified

If you need a cost-effective solution to facilitate information exchange over leaky feeder, ensure that it meets the stringent certification standards for hazardous and non-hazardous environments around the world.

6. It pays to get a total solution

A patchwork of communications and safety solutions from different suppliers is never as effective as a single system that provides location and detection, asset monitoring, collision prevention, air quality control or trapped miner search solutions from a single supplier.

7. Make it simple for operators

Ease of installation, operation and maintenance should be key criteria when buying an underground voice, video and data communications systems.

8. Two-way communication is vital

Two-way data communication is important because it allows operators to monitor and control various configurations of generic programmable logic controller (PLC) and custom application receiver/transmitter unit (RTU) equipment. Your solution should support master-slave or peer-to-peer operation. In addition to this, video channels should provide one-way real time video transmission from a remote camera to a video monitor, and the camera should have a complete range of controls, including zoom, pan, tilt; one data channel is required.

9. Easy integration with existing leaky feeder backbone

Save money and time by selecting safety solutions that can be integrated effortlessly into any existing leaky feeder communication backbone to establish advanced tracking, location and search application for mines and tunnels.

10. Tunnel operations require tunnel communications and safety solutions

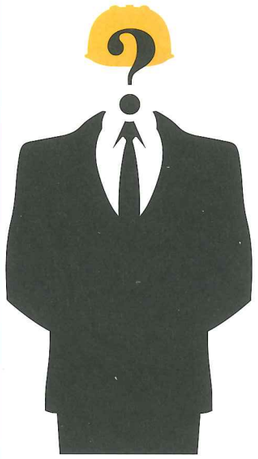
Ensure that any safety or communications system you buy for a tunnel construction project or an operating tunnel includes two way VHF, UHF and Ethernet solutions for voice, data and video, and that anything you buy is compliant with relevant tunneling industry standards and requirements.

11. Easy upgrades or expansions

Since it's inevitable that your communication and safety system needs are going to evolve over time, ensure you have equipment and technology that your operators can effortlessly upgrade or expand.

12. After sale support is vital

It's important to have the peace of mind that comes with knowing that the supplier of your communications and safety solutions has a team of communication specialists, technicians and engineers available to answer all solution and application questions.



Tweets for tunnels

"Excuse me sir! Do you mind switching off your Blackberry, we're about to take off." It's a wired up world where we communicate constantly and always worry if no one has emailed us in the last 10 minutes.

Yes, we can moderate our time on the amount of emailing we do, but behind it all is a public demand to be informed in a timely manner – which usually means now.

Clients want to know, our bosses want to know, our employees and teams want to know what's going on in addition to us getting on and building our projects. The time taken in the planning and environment consent stages of project development, or as construction is carried out, reflects society's need regarding information flow. And we shouldn't as a profession be surprised by this. So our Blackberry moments are a reflection of the greater world appetite for communication.

We might complain about the time taken up with public, projects or management to communicate, but it's a feature of our lives and it's here to stay.

We are not as good as we need to be. Letting the public know about what we do will raise awareness of how engineers are working to improve peoples lives in urban areas. Talking about what we do will raise public confidence in our work especially when the construction of projects impacts on urban society.

In the next 10 to 15 years in the tunnelling and underground space industry we will be doing a lot of work around the world. We are going to be extending our metro systems, building high speed railways in urban areas, building conveyance and network tunnels for water, stormwater and sewerage. We will be working on high profile intrusive infrastructure projects that will affect the public during construction, but inevitably will improve their daily lives. And the improvement of public life is something that we as an industry ought to press home when we inform the public of what we do. We should temper the negative short-term construction inconvenience with the positive message of long-term benefits.

We're not just building projects. We are improving mobility with metros, public health with water conveyance, mitigating effects of climate change with the storm water tunnels, or harnessing renewable energy with hydro projects. That's the story we need to tell the public. Doctors save lives and improve our health; teachers educate tomorrow's employees and improve the mind and maybe inspire us to greater learning; Architects can design and improve quality of the built environment. So civil engineers should be seen as providing solutions to global infrastructure problems. Our tunnelling industry should be seen as being part of the solution to global problems in urban areas.

In 2011 the world population in urban areas moved above the 50 per cent mark. By 2050 it will be at 70 per cent. Managing space is going to be the challenge of growth. Planners can only extend the urban boundaries so far in order to provide a viably run municipality. So urban sprawl has its physical and tolerable limits. You can build up and provide structures of dizzying heights and complexity. But some things cannot be at surface or above surface – certainly not if you are going to provide an acceptable living environment that will attract people to work and live in these urban areas. Countries such as Hong Kong and Singapore know that now and are about to follow the example of Helsinki, Finland and incorporate the use of underground space within their urban master plans. Space will be reserved for treatment plants, storage, commercial use, industrial use, and secured facilities. The municipality's role will be to zone this reserved space and to locate it where the geology can accommodate the use of the underground.

When they are informed about the attractiveness of using underground space the public have a negative perception of the concept of strategic public use of the underground space beyond conventional uses such as urban metros. But if properly explained, the public can see how underground space can provide solutions to future stresses on urban life. Our industry needs more proactive and positive messages to owners, politicians, government, developers and the public about the benefits of what we are providing for the future and the strategic benefits of underground space. If we start using language that supports this aim then we can only raise the awareness of our sustainable contributions to society.

So when in future you are asked: "What do you do?" The answer is not soley: "I'm a shift engineer on the construction of the London Crossrail project, or a "project manager on Himalayan Hydro tunnels." Just remember its not just about what you are doing now that should be the sole response. It should additionally be about what this does to improve the quality of life, whether its about mobility, public health, urban or energy solutions. Communicate this type of message and it will help raise our profile.

Communicate it always for consistency and don't be shy and apologetic about it.

We joined our industry and profession in underground engineering because we were enthusiastic about civil engineering and we wanted to build things with likeminded people. Let's now complete the message that it is not just about us; it's about solutions for society.

The message is that we work with society and nature to provide infrastructure to improve the quality of life for society. Think about that and believe it and the public will believe it too.

So go out and communicate more: tweet, text, surf, twitter, Skype, app, download and upload … and 'virtually' be damn'd.

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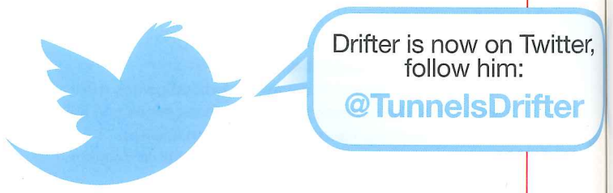

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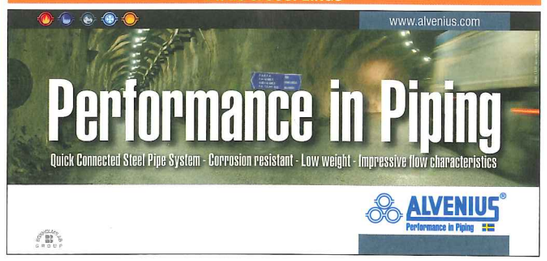

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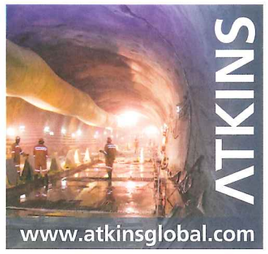

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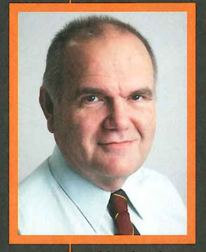

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