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TUNNELING & UNDERGROUND CONSTRUCTION

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Istanbul Strait road tube

Brisbane Airport link

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COVER STORY

In this issue — The Istanbul Strait road tube crossing was one of the most challenging underwater projects in the world. The challenges, risks and strategies used in boring the tunnel are discussed on page 7. Construction of the Brisbane Airport link project is examined on page 15. Cover photo shows the Istanbul Strait tunnel.

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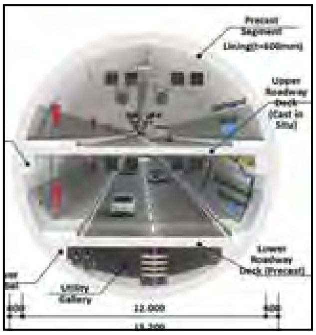

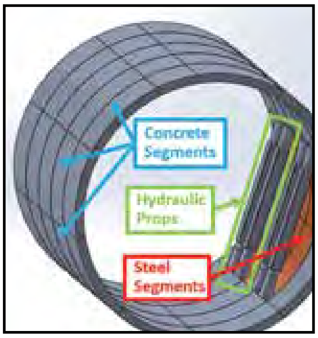

DEPARTMENTS

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CHAIRMAN'S COLUMN

The UCA of SME and the industry are in good hands

As I am writing this, I am watching the snow fall in mid-February. Local construction of igloos and snow caves has begun.

Over the last few weeks, I have been happy to learn from several of our members that opportunities for additional business have increased, and that current projects are continuing toward completion. Great news for the industry and for the public (the end users of our efforts), the benefits of which will be seen for years to come. At the same time, the use of underground space continues to become a more everyday practice, favored by the people once they see our results. We must continue on our journey to reinforce the benefits of our work to all we come into contact with.

In January, the UCA of SME hosted its annual George Fox Conference in New York City, at City College. As usual, there was a full house, ready to learn from the presentations and discussions, and to network with other attendees, many of whom they may not have seen or talked to since last year's conference. Our keynote speaker, Ed Plotkin was, as usual, wonderful and right on target with his points and insights. My thanks to our conference leaders, and to the UCA of SME staff, for their work and effort, making it a success once again.

Our next event will be the RETC, held June 4-7 at the Manchester Grand Hyatt in San Diego, CA. The conference should be just as fruitful as the previous events, providing the attendees with the most up to date information about our industry's most exciting projects, insights into our technological advances, and another opportunity for networking with peers. The following week, the ITA will sponsor WTC 2017 in Bergen, Norway. I have been in contact with several of the organizing committee members, and they have advised that the event will be as spectacular as ours was last year.

At the January UCA Executive Committee meeting following the Fox Conference, the committee reviewed recommendations for a new chairman, vice chairman and committee members. I am happy to report that Mike Roach was selected to be our next chairman. Bob Goodfellow was selected to be vice chairman, and Mike Vitale, Ted Dowey, Paul Schmall and Pam Moran (second term) were selected to be committee members. Congratulations to all. I want to thank Lester Bradshaw and Kellie Rotunno for their many years of service on the executive committee. Also, many thanks to Bill Edgerton for his work as Past Chairman for the last two years. All of these people have provided much valuable guidance and direction to our association. Their efforts and accomplishments are much appreciated.

I am very pleased to finally announce that our book, the *History of Tunneling in the United States*, has been completed, and will be printed and distributed in early April, 2017. All WTC 2016 registrants will receive a copy, and additional copies will be available from the UCA. I am sure that the book will be well-received by all, and would be a nice gift for all industry members, clients and other government officials. Underground aficionados are sure to enjoy it as well. Thank you to all of the writers, editors, photographers and other contributors.

I would like to remind all of our members about the 2017 ITA Awards event in Paris, France, and suggest that all members consider submitting

(Continued on page 5)

Federal government commits $1.5 billion to LA Metro expansion project

Federal and local officials announced roughly $1.5 billion in new grants and loans for the second phase of the Los Angeles's Metropolitan Transportation Authority expansion project. Specifically, the funds will go toward the completion of the Purple Line subway that will eventually run the length of Wilshire Boulevard to Westwood.

The Metropolitan Transportation Authority project has relied on matching funds from the federal government along with voter-approved sales taxes for the project.

Los Angeles Mayor Eric Garcetti celebrated the funding announcement, saying he doesn't expect the funding to change with the transition to President Donald Trump's administration.

"We feel strongly that this is a bullet-proof agreement and one that'll move forward in the interest not just of Los Angeles, but of America," Garcetti said at a press conference in Century City. "This is something people understand is not politics, it's not ideology— it's about getting people moving."

The U.S. Transportation Secretary Anthony Foxx joined Garcetti and Metro officials in making the announcement.

The $1.487 billion agreement between the federal government and Metro calls for a $1.187 billion construction grant through the Federal Transit Administration's Capital Investment Grant program along with a $307 million loan from the Department of Transportation. Metro will also receive another $169 million in federal funding to mitigate congestion and address air quality.

The federal dollars will be added to $836 million in local matching revenues from Measure R and Measure M, sales tax increases approved by voters, bringing the budget for the second section to about $2.5 billion.

> **"We feel strongly that this is a bullet-proof agreement and one that'll move forward in the interest not just of Los Angeles, but of America."**
>
> ***Los Angeles Mayor Eric Garcetti***

The first phase of the project, extending the line to stations at La Brea Avenue, Fairfax Avenue and La Cienega Boulevard is already underway at an estimated cost of $2.64 billion, including more than $2 billion in federal grants and loans.

The full length of the Purple Line to the Veterans Administration hospital just west of UCLA is slated to be completed in 2035 but could be accelerated by 10 years with funds from Measure M and possible private partnerships. ■

Unsolicted proposals could advance Measure M project in Los Angeles

LA Metro announced that four unsolicited proposals that could accelerate two mega projects included in Metro's Measure M transportation ballot measure have advanced from Phase I to Phase II analysis. Two of the proposals are for the West Santa Ana Branch Transit Corridor and two are for the Sepulveda Pass Transit Corridor. Each proposal suggests a different approach to bringing innovation, acceleration, cost savings and/or other benefits to the respective projects, compared with Metro's planned project delivery method.

The four proposals have passed the initial conceptual review – as outlined in Metro's new unsolicited proposal policy — and will move on to the second phase in the process: a more detailed qualitative and quantitative analysis.

The two proposals for the West Santa Ana Branch Transit Corridor moving forward in the process are from Skanska (Skanska USA Civil West) and Kiewit (Kiewit Infrastructure West Co.). Two others are for the Sepulveda Pass Transit Corridor. They are from Parsons (Parsons Transportation Group, Inc.) and Cintra (Cintra US Services LLC, an affiliate of Cintra Global Ltd.).

Following a detailed analysis of the Phase II proposals, Metro staff will decide whether to issue requests for proposals to the industry.

In February 2016, Metro hosted the agency's first major industry forum, Transformation Through Transportation. That's when Metro officials invited the private sector to bring the agency their ideas for helping Metro deliver projects sooner than they are scheduled.

Throughout the year, Metro has been accepting unsolicited proposals on various levels and for different ideas. These are the first mega projects to advance to Phase II analysis. ■

Tesla founder hints at joining tunnel boring industry

What started with a traffic jam in Los Angeles might end up becoming a new company in the tunnel boring sector that is backed by billionaire entrepreneur Elon Musk.

Musk, the man behind Tesla cars and Space X, a Los Angeles-based company that designs, manufactures and launches advanced rockets and spacecraft, tweeted that he was fed up with traffic and that he was going to "build a tunnel boring machine and just start digging."

And now it appears that he was serious. According to an article published by *Wired* magazine, crews have excavated a "test trench" 9-m (30-ft) wide, 15-m (50-ft) long and 4.5 m-(15-ft) deep on the grounds of SpaceX's Los Angeles headquarters. Musk calls it the beginning of an experiment. "We're just going to figure out what it takes to improve tunneling speed by, I think, somewhere between 500 and 1,000 percent," he told *Wired* during a hyperloop design competition at SpaceX. "We have no idea what we're doing — I want to be clear about that."

Wired reported that in a conversation with Musk, he expanded on the thoughts of the tunneling and said "if you think of tunnels going 10, 20, 30 layers deep (or more), it is obvious that going 3D down will encompass the needs of any city's transport of arbitrary size.

"You have tall buildings, they're all 3D, and then everyone wants to leave the building at a same time," he said. "On a 2D road network, that obviously doesn't work, so you have to go 3D either up or down. And I think probably down."

Musk doesn't need permission to dig on company property, but is working with the city on plans for a pedestrian bridge or tunnel so people can safely cross the wide thoroughfare alongside the campus.

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Robbins TBM overcomes challenges on high-cover Los Condores hydroelectric project

Chile's Los Condores Hydroelectric Project (HEPP) is a high-cover, hard-rock challenge, with 500 m (1,640 ft) of rock above the tunnel and a high-altitude jobsite 2,500 m (8,200 ft) above sea level. As of January 2017, a 4.56-m (15-ft) Robbins double shield tunnel boring machine (TBM) had completed boring its 900 m (2,950 ft) long access tunnel and was well on the way to boring the first section of headrace tunnel. The machine embarked on its journey on May 27, 2016, and has since excavated more than 1,300 m (4,270 ft) of tunnel in total.

The journey to machine launch was an arduous one, requiring shipment of TBM components and vehicle transport on unpaved, mountainous roads. Contractor Ferrovial Agroman is responsible for the intake tunnel at the Los Condores Hydroelectric Project, and was well aware of the challenges associated with machine launch: "The location of the work is a big constraint due to its rugged terrain and geographical location in the Andes. With all this, we are anxious to perform work in an efficient manner," said Pello Idigoras, tunnel production manager for Ferrovial Agroman.

The jobsite, located 360 km (224 miles) south of Santiago, Chile, is part of a new 150-MW power plant and intake tunnel. The Robbins double shield TBM is boring two sections of the intake tunnel, the first measuring 6 km (3.7 mile) and the second measuring 4.4 km (2.7 miles). A section between the two tunnels will be excavated by drill-and-blast to connect them, making the intake tunnel about 12 km (7.5 miles) in length. "This project brings an increase in energy production in the country, thus contributing to the overall improvement in the welfare of its citizens," said Idigoras of the effect the completed hydropower project will have on surrounding areas.

The challenging launch of the Robbins TBM at the remote jobsite 2,500 m (8,200 ft) above sea level.

The tunnel, located in the mountainous Maule region of Chile, is being bored in two types of rock: sedimentary and volcanic. The rock has been tested at strengths up to 100 MPa (14,500 psi) UCS, with at least two fault zones — the first of which has already been traversed in rhyolite, andesite, tuff, and breccia. For Idigoras, the conditions are well-suited to double shield tunneling: "We have good quality medium to hard rock for double shield excavation overall," he said. Despite that, some areas of challenging ground persist. To cope with the conditions, including steadily increasing water inflows at rates of up to 3,500 l/min (925 gpm), the contractor is utilizing cementitious grouting and chemical grouting with polyurethane and foam. Such ground conditioning techniques were anticipated and the Robbins double shield was designed to effectively apply these techniques.

As the TBM excavates, it is lining the tunnel with 250 mm (10 in.) thick, 1.2 m (3.9 ft) long concrete segments in a 4+1 arrangement. The machine is currently progressing at a rate of up to 25 rings per 20 hours of boring. Crews are operating in two 10-hour shifts with one 4-hour shift dedicated to maintenance. Idigoras sees the TBM performance and completion of the access tunnel as huge project milestones, though much work remains to be done. "After many months working in engineering, manufacturing, installation and commissioning, we are proud to see this result. It would be impossible to name all the people who participated in this project thus far but they, as a whole, have managed to get the TBM started digging and boring well." ■

Chairman's Column: Thanks to many for their support along the way

(Continued from page 2)

nominations through the UCA for consideration. The past two years' events were wonderful, and many fabulous projects were highlighted. We Americans have worked on many worthy projects that deserve to be submitted for evaluation by the ITA on their merits.

Lastly, I want to thank all of you for your support over the last two years during my time as Executive Committee Chairman. I appreciated the work of all the committee and event members, the UCA staff, and the association in its entirety. I am proud to have represented each and every one of you, and will continue to work to promote the group, and help wherever I can.

Artie Silber,
UCA of SME Chairman

Herrenknecht's direct pipe technology passes the test in Poland

In the fall of 2016, drilling contractor PPI Chrobok S.A. installed two new gas pipelines in Poland. The alignment runs along existing gas lines and through geologically challenging terrain. With the laying of the 700-m and 464-m (2,300-ft and 1,522-ft) long pipelines, Herrenknecht's direct pipe technology was used in Poland for the first time.

With the construction of a new north-south pipeline connection, Poland is reacting to the increasing local demand for gas. Part of this network expansion is the Czeszów-Wierzchowice Gas Pipeline Project in the southwest of the country. So far, only technology horizontal directional drilling (HDD) had been used for crossing rivers or roads during pipeline projects in Poland. However, the sandy, sticky clay of the pipeline crossings in Wierzchowice and Czeszów presented the drilling crew with challengs that could not be met with HDD methods. Furthermore, the two alignments with lengths of 700 m and 464 m (2,300 ft and 1,522 ft), respectively, run along existing gas lines. Uncontrolled deviations during the drilling process thus had to be avoided at all costs. In view of these requirements, for the first time main contractor PGNiG Technologies S.A. together with drilling contractor PPI Chrobok S.A. opted for the innovative Direct Pipe technology from Herrenknecht. This method combines the advantages of microtunnelling and HDD technology. In a single step the required borehole is created and the prefabricated pipe is simultaneously installed without a trench.

Thanks to the gyrocompass navigation system that allows for an exact steering of the tunnel boring machine, the drilling crew precisely installed the two pipelines with an outer diameter of 1.047 mm (0.5 in.) underground in just 13 and 16 drilling days, respectively. In doing so, they safely crossed, among others, beneath an ecologically sensitive fish pond. The sticky ground that typically tends to cause blockages is not a barrier for the direct pipe method. Even at very high levels of friction resistance, the 500 t (550 st) of thrust provided by the pipe thruster in the launch shaft is more than enough. Despite the small overcut of only few centimeters, no damages were detected at the coating after the pipe laying. The project achieved a daily best performances of 147 m (482 ft). ■

Tesla: Musk said to be eyeing better tunnel boring machines

(Continued from page 4)

But extending the shaft all the way to Los Angeles' airport — as Musk has threatened to do — would require more discussion, paperwork, and LA City Council approval, says a spokesperson for the LA Department of Public Works.

Of course, if Musk intends to expand on his tunneling efforts, things will get much more complicated once his project leaves the Space X campus.

The LA Metro has dealt with the challenges first hand as it works to connect its three rail lines.

Asked about these alternatives, Musk said, "better tunneling tech improves everything: road, subway, Hyperloop." ■

Colorado School of Mines to offer tunneling and underground courses

Registration is now open for underground construction and tunneling short courses at Colorado School of Mines' Center for Underground Construction and Tunneling.

These short courses are designed for industry professionals including owners, planners, designers, contractors, consultants and suppliers involved in the planning and construction of underground, tunneling and mining projects. Space is limited and discounted registration rates are available for a short time.

In June 2016, the Tunneling short course attracted 150 participants.

The courses include outstanding lectures and case studies presented by industry experts along with hands-on labs and demonstration. These courses provide tremendous value to all who attended.

Colorado School of Mines has a long-standing tradition of hosting world-class short courses on its campus in scenic Golden, CO, creating unique opportunities to learn, network and earn CEUs.

Learn more and register online at underground.mines.edu, or call 303-384-243.

Underground Grouting and Ground Improvement

May 1-5, 2017, directed by Raymond Henn and Reza Hedayat.

Tunneling Fundamentals, Practice and Innovations

September 18-21, 2017, directed by Mike Mooney and Gabe Walton. ■

FEATURE ARTICLE

Istanbul Strait road tube crossing: Challenges, risks and strategies

FIG. 1

Project alignment.

The 13.2 m (43 ft) external diameter, double deck Istanbul Strait Road Tube Crossing is one of the most challenging underwater tunnel projects in the world. Subjected to 11 bars of hydrostatic pressure, variable geology, and being in a very active seismic area, the execution of the project required innovative solutions, sophisticated construction techniques and prudent risk management approach. The 5 km (3.1 mile) tunnel consists of a 3.4-km (2.2-mile) tunnel boring machine-(TBM) bored tunnel, 1 km (0.62 mile) twin NATM tunnels and cut-and-cover sections. The project is being delivered in a build-operate-transfer (BOT) contract in a public-private partnership. The technical challenges, coupled with financial and commercial risks required the implementation of sophisticated risk management tactics including the provision of independent design verification. The project was opened to traffic on December 20, 2016, four months ahead of schedule.. This article presents the technical challenges of the project from the design, construction, and risk management aspects..

Nasri Munfah, Sanja Zlatanic, Gordon Clark, Basar Arioglu and Tolga Togan

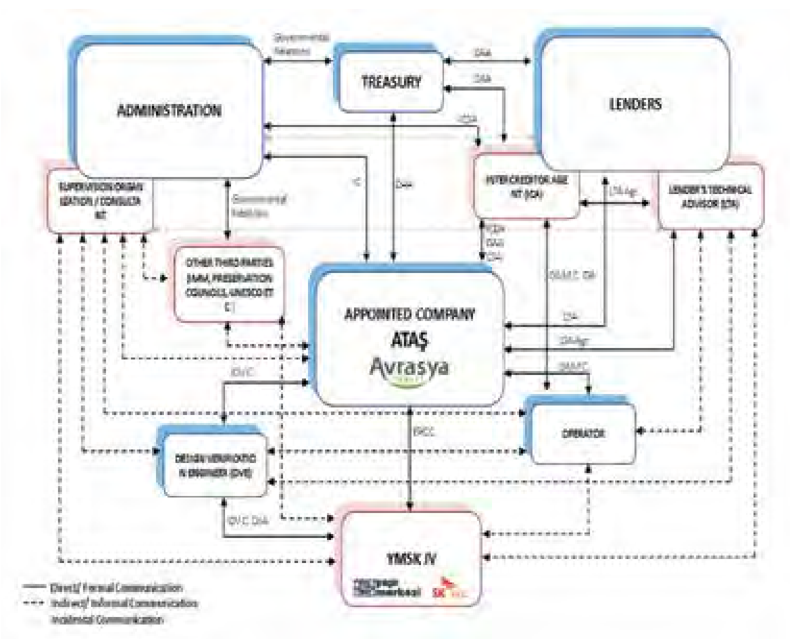
Nasri Munfah, Sanja Zlatanic, members UCA of SME, are Sr. vice president/ director of global tunneling and project manager, HNTB Corp. New York, USA **Gordon Clark,** member UCA of SME is assistant vice president, WSP/Parsons Brinckerhoff, Seattle, USA **Basar Arioglu,** member UCA of SME is manging director, Yapi Merkezi Construction Inc., Istanbul, Turkey and **Tolga Togan,** member UCA of SME is technical manager, WSP/Parsons Brinckerhoff, New York, USA, email munfah@pbworld.com.

Project background

The $1.245 billion Istanbul Strait Road Tunnel Crossing project, dubbed the Eurasia Tunnel, is one of several major infrastructure projects being implemented in the Republic of Turkey in a public-private partnership approach. The project provides a direct and easy connection between the Anatolian (Asian) side of Istanbul and the heart of its historical district on the European side across the Bosphorus Strait which connects the Black Sea with the Sea of Marmara. The project improves connections to a wide network of motorways on both sides, increase capacity across the Bosphorus by 100,000 vehicles a day, reduces congestion and saves motorists an average of 45 minutes of commuting time in each direction bringing significant economic benefits to the city and the region. It eases traffic across the strait, reduces congestion, decreases pollutants and emission while maintaining

FIG. 2

Project stakeholders relationships.



the historical silhouette of the city. Figure 1 provides a general view of the project location and alignment. The overall project consists of three parts totaling 14.6 km (9.1 miles). Parts one and three consist mainly of widening existing motorways, providing connections to existing roads, reconstructing local bridges and underpasses on the European and Asian sides respectively. Part two is the tunnel crossing across the Bosphorus. It is the most complex part of the project with the greatest challenges and risks. Part 2 is 5.4 km (3.6 miles) long consisting of 3.4 km (2.2 miles) of 13.2 m (43.3 ft) external diameter TBM bored tunnel under the Bosphorus Strait, 1-km (0.62-miles) of twin NATM tunnels on the Asian side, cut-and-cover transition boxes in the Asian and the European sides and depressed approaches on both sides. In addition, this segment includes the toll plazas, ventilation buildings, and the tunnel control and maintenance facilities.

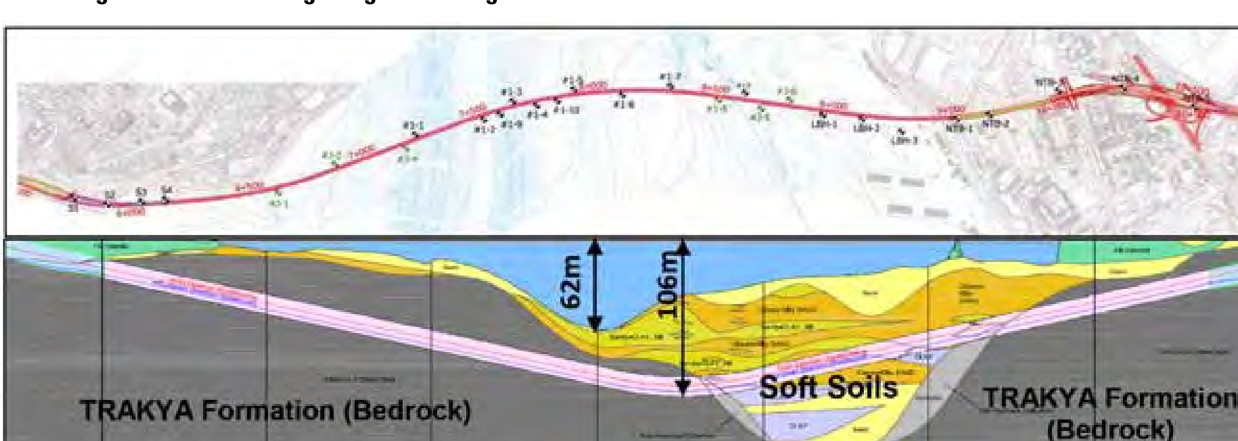
Public-private partnership achieves successful execution of needed infrastructures

The employer, the Ministry of Transport, Maritime Affairs and Communications, and Directorate General of Infrastructure Investments (AYGM) selected Avrasya Tüneli Isletme Insaat ve Yatırım A.S. (ATAS), a joint venture of the distinguished Turkish firm Yapı Merkezi (YM), and the experienced Korean firm of SK Engineering and Construction Co. Ltd. (SK E&C) as the project concessionaire to build and operate the facility for a concession period of 26 years. Each of these two firms is well-known for its successes in large-scale infrastructure and transportation projects in their respective market sectors. With a total investment of $1.245 billion of which about $300 million is in equity, ATAS is committed to start the tunnel operation within 48 months from the financial closure.

Figure 2 shows the project stakeholders

FIG. 3

Project configuration meets the geological setting.



relationships.

The project financial closure took place in March 2013 and the tunnel operation is anticipated to start in March 2017.

To implement the project, ATAS assigned the joint venture of Yapi Merkezi and SK E&C (YMSKJV) to design and construct the project. A global team of top engineering firms were assembled to tackle this unique and challenging project including Parsons Brinkerhoff as the lead designer, HNTB as the independent design verifier (IDV), Fugro for the geotechnical studies, Herrenknecht as the TBM supplier, Yapı Merkezi Prefabrication as the segment producer and Egis as the facility operator among many other local and international firms.

The sub-sea single TBM tunnel passes through weathered bedrock (Trakya Formation) on either side of the Istanbul Strait and through alluvial deposits including sand and gravel near mid channel. The TBM tunnel was bored to a depth of 106 m (348 ft) below the water surface requiring it to resist 11 bars of hydrostatic pressure and up to 22 bars of hydrodynamic pressure during a severe earthquake. The stacked tunnel transitions on the Asian side in the Asian Transition Box, a cut-and-cover structure 168m (551ft) long and 35m (115ft) deep, to twin NATM tunnels approximately 1-km (0.62-miles) long each excavated in the Trakya Formation. The bored stacked tunnel transitions to two cut-and-cover tunnels in the European Transition Box. Tunnel portals on either side were constructed using cut-and-cover methods in alluvium soils and total about 1-km (0.62 miles) in length. The tunnel plan and profile are shown in Fig. 3.

Bored tunnel cross section. The TBM bored tunnel was designed with stacked roadways that included emergency walkway and emergency alcoves. Figure 4 illustrates the layout of the stacked roadways in the TBM bored tunnel. The tunnel nominal outside diameter of 13.2 m (43.3 ft) and 12 m (39 ft) inside diameter provided space for two, 3-m (10-ft) wide travel lanes in each direction and a 1.2-m (4-ft) wide emergency egress at each level. The 3 m (10 ft) vertical clearance allowed for cars, vans and mini busses only. Emergency egress stairways were provided every 200 m (656 ft) into pressurized stairwells connecting the upper and lower roadways; and vehicular breakdown alcoves were provided every 600 m (1,968 ft). Longitudinal ventilation was provided by jet fans in the ceiling of each roadway supplemented by two ventilation buildings. In addition, all other essential elements including traffic control, lighting, communication, etc. were provided in each traffic level. The upper roadway was cast in-situ and supported by cast in-situ concrete corbels on either side that are anchored into the precast segmental tunnel lining through the use of grouted steel dowels. The lower roadway deck was formed

FIG. 4

Bored tunnel.

with precast concrete panels resting on similar corbels. The space beneath the lower deck accommodated the cableways, sump pumps, water and drainage systems, and other utilities supporting the tunnel operation.

The tunnel was constructed using concrete precast segmental liner 600-mm (23.6-in.) thick, 2-m (6.6-ft) long double reinforced with a compressive strength of 50 MPa (7000 psi) and equipped with double 37 mm (1.4 in.) EPDM gaskets. Each ring consisted of eight segments and a key. The individual segments were connected using spear bolts in the circumferential and the longitudinal joints. Guide rods were used between rings to assist ring build accuracy. Cam and sockets were included on circumferential joints to assist in achieving

FIG. 5

NATM tunnel cross section.

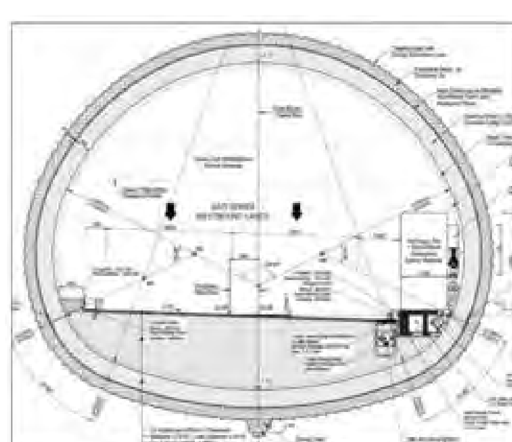
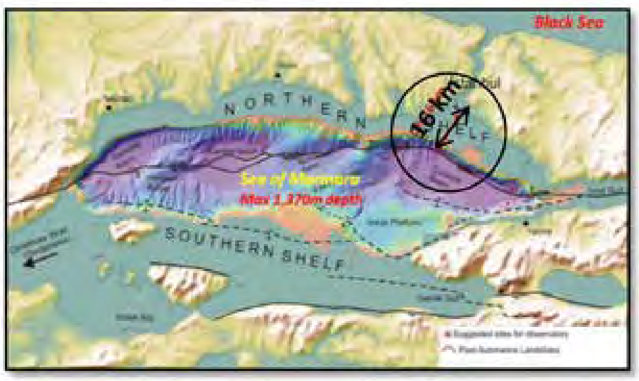


FIG. 6

Close proximity of the project site to the Marmara Fault increases the risk of seismic impact.



ring-build accuracy and to provide supplementary support for segments during the ring building operation.

NATM section. The NATM section provides a connection between the Asian Transition Box and east portals extending 930 m (3,051 ft). The twin NATM tunnel cross section has a typical curvilinear configuration including the invert due to poor ground conditions and the high hydrostatic pressure (Fig. 5). The two NATM tunnels are very close to each other with a limited pillar on the western end, but they diverge as they extend eastward. The twin NATM tunnels include four cross passages, a lay-by area for disabled vehicles and four mechanical and electrical rooms. The construction of the NATM tunnels was done by top heading, bench and invert using pre-support arch canopy to deal with the poor ground conditions. Near the portals, the cover over the tunnels is limited requiring special pre-support measures and rigorous monitoring. The initial liner consisted of 200 mm (7.8 in.) shotcrete over lattice girders and rock bolts. The final liner is cast in-situ 400 mm (15.7-in.) reinforced concrete over fully encapsulated PVC waterproofing membrane system.

Geotechnical investigations define subsurface conditions

The bedrock underlying the tunnel alignment is the Trakya Formation, a sedimentary rock composed of inter-layered siltstones/mudstones and sandstones. Generally, there are three primary joint sets in the Trakya, with the siltstone/mudstone exhibiting additional random jointing not observed in the sandstone. One joint set is approximately horizontal and the other two are oriented approximately orthogonal in a NW-SE and a NE-SW direction. The dip angle of the latter two joint sets is relatively steep, varying from approximately 65° to 85°.

The sedimentary rock of the Trakya Formation has been intruded by igneous dykes of diabase, andesite, or dacite. Based on observations at the adjacent Marmaray rail tunnel project, the igneous dykes occur at a frequency of approximately 70 m to 150 m (230 ft to 492 ft) with variable thickness up to 20 m (66 ft). The rock adjacent to the intrusive dykes is more intensely fractured and weathered than the unaltered bedrock. Soft ground is alluvial deposits ranging from coarse-grained soils (gravels and sands) to fine-grained soils (silts and clays) and can vary both vertically and laterally as a result of depositional history. The TBM tunnel passes through mostly silty fine sand and some clay and sandy clay layers. Gravel and cobbles are encountered at the interfaces between the Trakya Formation and the alluvial soils. Figure 3 shows the geological stratigraphy.

The geotechnical investigations included 17 offshore borings taking undisturbed tube samples in soil and core samples, RQD, and drilling rates recorded in rock. Several offshore borings included sonic logging to determine dynamic properties of the soil and rock. Offshore investigations also included a 3-D high-resolution shallow seismic geophysical survey, extending from approximately 50 m to 100 m (164 ft to 328 ft) to either side of the tunnel alignment to define soil stratification and top of rock surface along the crossing. Extensive laboratory and in-situ testing was performed including hardness tests, abrasion tests, slake durability tests, and P and S wave velocity determinations, among others.

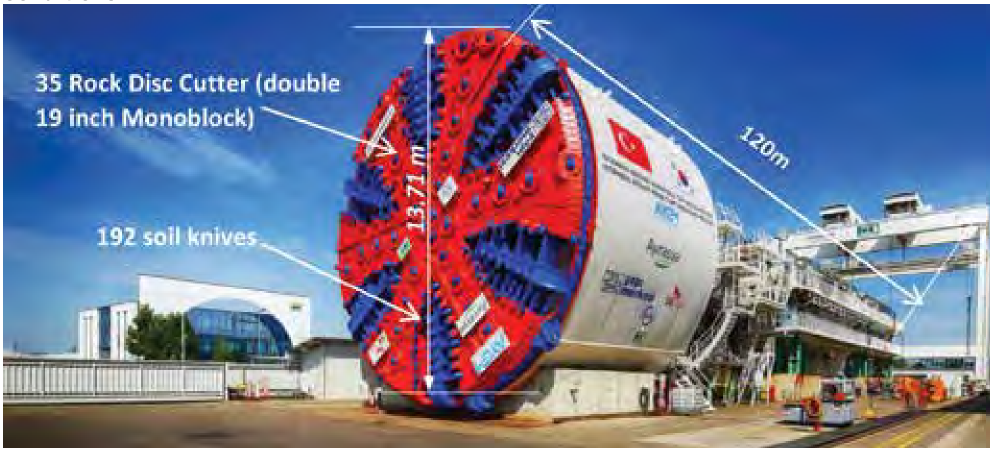
Seismic conditions. Istanbul Metropolitan area falls within three tectonic plates: the African, the Anatolian and the Eurasian plates. The collisions of these plates have resulted in the formation of complex fault systems in the area with the Marmara fault being the most prominent and most active. The project site lies about 16 km (9 miles) from the Marmara fault as shown in Fig. 6, therefore a thorough assessment of the risks associated with a potential earthquake is very important for the safety of the tunnel. To address the high seismic risk, the employer specified a performance based design earthquake approach using a functional evaluation earthquake (FEE) with a 20 percent probability; and a safety evaluation earthquake (SEE) with 4 percent probability of occurrence during the 100-year design life of the tunnel. The FEE and SEE generally correspond to design seismic events with return periods of 500 and 2,500 years respectively. The project-specific seismic hazard assessment defines the design earthquake magnitude as 7.25 (moment magnitude) and source-to-site distance as 16 km (9 miles) for both SEE and FEE. Under the SEE earthquake, life safety should be ensured and continuous operation of the facility with slight to no damage to structures; while for the FEE earthquake, life safety should be ensured and any structural damage should be repairable within a reasonable period.

Best practices provide good risk management

The project variable geology, hydrology, and susceptibility for high seismic activity combined with high water pressure and the large diameter/double-deck configuration make the Eurasia Tunnel one of today's most challenging and complex tunneling projects in the world. To address and mitigate the various risks, ATAS implemented a pro-active risk management plan from the initial design development stage through final design and construction. An essential element of the plan was the implementation of an independent design verification process..

FIG. 7

Eurasia tunnel TBM was designed to handle high water pressure and difficult ground conditions.



Independent design verification (IDV) process. As part of the independent verification process, detailed reviews and independent analyses and checks were performed for category three structures (per Eurocode) and for all other critical elements of the project. To assure quality performance and to mitigate potential risks, the independent verification was extended to cover all other major elements and disciplines including verification of the tunnel alignment, the tunnel major mechanical and electrical systems and services including power, lighting, hydraulics, tunnel ventilation, fire life safety, communications, architectural and space planning, traffic control and system integrations, as well as facility operation. The goal was to verify compliance with employer's requirements and with design codes and standards. Furthermore, the IDV reviews included potential value engineering ideas and betterments to improve construction cost and/or schedule.

The verification of the basic design assured that the design was brought to a sufficient level of completion to enable YMSKJV and the employer to evaluate the inherent risks. In the detailed design, the final calculations, drawings and technical specifications were verified. The independent verification included independent calculations for most critical components including the bored tunnel, seismic analyses, NATM tunnels, transition structures, cut-and-cover tunnels, retaining walls, U-sections, portals, temporary support of excavation, systems and buildings, ventilation analyses and alignment and drainage calculations. The IDV reviews have determined that the design complies with the employer's requirements and design criteria, met codes and standards, reduced construction risks, improved constructability, increased safety and efficiency of the facilities and decreased operational costs. The IDV role also addressed project risk elements and recommended solutions/approaches to mitigate design related risks. After both the basic and the detailed designs were verified, a design verification certificates (DVC) were issued allowing YMSKJV to proceed with the construction of the verified packages and to obtain the employer's and lenders' approvals. The role of the IDV provided ATAS the mechanism for self-certification, provided the employer assurances that the design meets its requirements and the project codes and criteria, and provided the lenders affirmation that the design meets its intended purpose and its requirements in support of their financial investments. This approach reduced potential risks to ATAS, to the employer and to the lenders.

Technical challenges and risks mitigated by the application of state-of-the-art technology

The following are the project's most critical technical challenges that required special attention of the design, the construction, and the independent design verification teams. Risks associated with these challenges were identified early and mitigation measures were implemented during the design and the construction in order to manage them.

The main project risks included the large tunnel diameter, the high hydrostatic pressure, the variable and difficult ground conditions, and the high seismic loading. To address some of these risks, a state of the art Herrenknecht's Mixshield TBM was specifically designed for the project. The TBM was designed to be capable to address the various ground conditions encountered and the high hydrostatic pressure as will be discussed. Figure 7 shows the project TBM. It is 13.71 m (45 ft) in diameter, 120 m (394 ft) long, and weighs

FIG. 8

Volcanic dyke in the Trakya based on Marmaray Tunnel experience.

3 kt (3,300 st). It is designed to handle 12 bar of water pressure and to deal with variable and mixed ground conditions. It had the applied power of 33 kW/m^2 (1st in the world).

Due to the high hydrostatic pressure, the TBM was designed to allow almost complete access to the back of the cutting wheel under atmospheric pressure. From there, all disc cutters and a large number of the soil cutting knives can be changed safely under atmospheric pressure. In addition, the TBM was equipped with air lock systems which allow access for compressed air works; furthermore, saturation diving using transfer shuttle, if needed, was provided.

The TBM design accommodated the high-face pressure and the differential pressure between the crown and the invert. In addition, the tailskin seal system consisting of three rows of wire brush seals and an inflatable emergency seal allowed the grouting of the annular space from within the tail shield. During TBM advance, grease is pumped between the wire brushes with a pressure higher than the backfill grout injection

FIG. 9

Tool replacement under atmospheric pressure.

pressure. This ensured a seal and maintained the face pressure.

Large bore tunnel. The Eurasia Tunnel being the sixth largest tunnel in the world, by itself, is a challenge. However, combining the large size of the tunnel with the various challenges already stated makes this tunnel construction one of the most challenging in the world. The tunnel cross section was developed in way to provide all needed functions in as compact arrangement as possible in order to reduce the overall diameter, yet accommodate all traffic and life safety elements. As indicated above, the design of the tunnel consisted of two traffic compartments each providing two standard lanes, and an emergency walkway (Fig. 3). Due to the tight geometrical configurations, the upper deck had to be constructed using cast in-situ, while the lower deck was constructed using precast units. In order to meet the overall project schedule, the construction of the interior structure progressed as the TBM tunneling was progressing.

The project geology that the TBM had encountered generally consists of the Trakya bedrock formation, described above, underlying alluvial sediments at the bottom of the channel.. The formation of the strait was formed by historic tectonic forces which left the Trakya bedrock folded, faulted, intruded, intensely fractured and weathered. Within the Trakya Formation, volcanic igneous dykes intrusions of diabase, andesite and dacite thick were encountered resulting in the presence of highly variable rock strengths, abrasive mineralogy, and the presence of stiff blocks embedded in soft matrix. Figure 8 illustrates the presence of a volcanic dyke in the Trakya Formation based on the nearby Marmaray Tunnel project. In addition, faults at various locations across and adjacent to the tunnel alignment were encountered. The alluvial deposits varied from gravels and sands to silts and clays. Cobbles and boulders are also present in the soil matrix especially at the interface between the Trakya Formation and the alluvial deposits. The TBM tunnel in the soft ground passes through mostly silty fine sand and some clay and sandy clay layers. Tunneling in mixed face conditions along the tunnel alignment was occurred in three potential geological situations: alluvial overburden materials overlying the Trakya Formation; interface between Trakya sedimentary bedrock and volcanic dyke intrusions, and fault zones passing through the Trakya. The top of rock varies in elevation as an undulating and inclined surface; therefore, the TBM was in and out of mixed face conditions for extended lengths.

The TBM was designed to deal with the variable ground conditions and the presence of volcanic dykes and boulders and cobbles. The TBM was equipped with 48 units of double 48 cm (19 in.) monoblock rock disc cutters in addition to 192 soil knives and a jaw crusher. The TBM operated in a closed face mode to control potential ground losses and to maintain face stability. Although abrasion did not present major problems, the high quartz content in the Trakya formation on the European side caused more frequent tool changes. The use of 48 cm (19 in.) discs cutters improved the disc lives and their rigidity. The TBM was able to handle the presence of the igneous dykes and the boulder zones in the transition zones with no loss of slurry.

Dealing with high hydrostatic head. The tunnel being subjected to 11 bars of water pressure requires special measures to be taken during construction and for the long term operation of the facility. Having such high water head and no ability to establish safe haven locations along the tunnel alignment, limited the ability of maintaining the TBM. Therefore as discussed above, the TBM was designed to allow all disc cutters and a large number of the cutting knives to be changed under atmospheric pressure. In addition, the TBM is equipped with an air lock system and saturation diving shuttle which allowed hyperbaric intervention as needed. Seven hyperbaric interventions with up to 10.8 bars were implemented during the tunneling operation. Figure 9 shows tool replacement under atmospheric pressure.

To deal with the high water head for the 100 year design life of the tunnel, the liner was equipped with two 37 mm (1.4 in.) EPDM gaskets on the intrados and the extrados to maintain water tightness during normal operation and in case of seismic movement.

Flexible joints accommodate severe seismic potential. The bored tunnel passing through rock and alluvial deposits was analyzed for transverse, ovaling and longitudinal deformations due to seismic event. The transverse ground deformation analysis consisting of one-dimensional free-field site response analysis at different sections along the tunnel alignment was performed to derive ground deformation profiles and strain-compatible ground stiffness as input to

FIG. 10

Results of seismic analyses and locations of seismic joints.

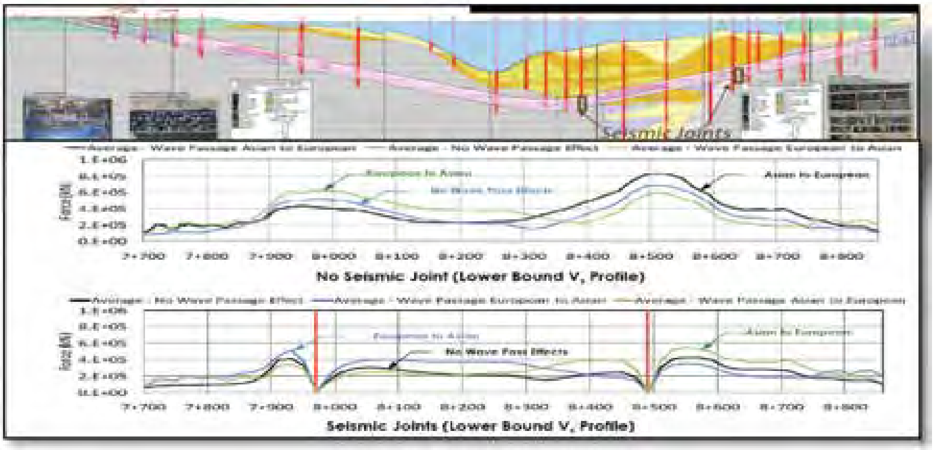


FIG. 11

Seismic joint model and the joint in place.

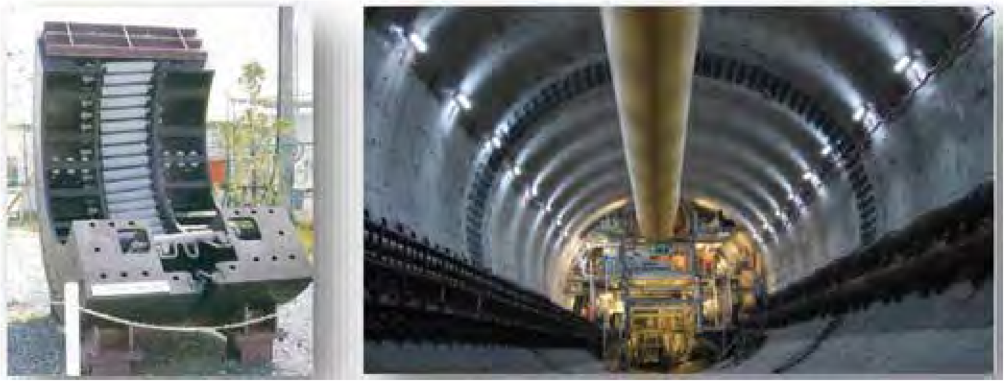


FIG. 12

TBM breakthrough.

the structural transverse analyses of the liner. The longitudinal tunnel and ground response analyses were performed using three-dimensional quasi-static beam-spring models. The three-dimensional free-field ground deformation-time histories evaluated from site-response analyses were applied at the support end of the ground springs to evaluate the tunnel-ground interaction. The strain compatible ground spring stiffness values were derived from quasi-static response analyses using a three-dimensional finite difference program. Figure 10 shows the results of the longitudinal forces. The results indicated that the placement of seismic joints at the interface between the rock and alluvial deposits reduces the seismic demands (axial force and transverse shear loads) to below the allowable levels. The seismic joints were designed with displacement capacity of ± 50 mm (2 in.) in shear offset and 75 mm (3 in.) in extension/contraction. The seismic joints were designed, fabricated, and tested in Japan to meet the performance requirements including design life, durability, sustained loads, and water tightness. Figure 11 shows the model of the joint and in its final position.

Conclusions

On Aug. 22, 2015, the Eurasia tunnel project has completed the most challenging phases of its construction with the TBM breakthrough. Figure 12 shows the TBM breakthrough in the European transition box. And the project was opened to traffic on Dec. 20, 2016, four months ahead of schedule..

It is proven that the project was set up from its very onset to incorporate multiple appropriate provisions to recognize, manage and mitigate construction and commercial risks. These provisions included the assembly of top level team, the inclusion of the IDV process, the selection of state of the art TBM, and the provision for risk management approach from the planning phase through construction and operation.

Acknowledgment

The authors of WSP/Parsons Brinckerhoff and HNTB Corp. wish to acknowledge ATAS and its member firms of Yapi Merkezi and SK E&C for the opportunity to work on this iconic project and for supporting the publication of this paper. Recognition is also given to the project team staff and to the subconsultants and their staff for their diligent work and efforts.

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FEATURE ARTICLE

Observed loading behavior during cross passage construction at the Brisbane Airport link project

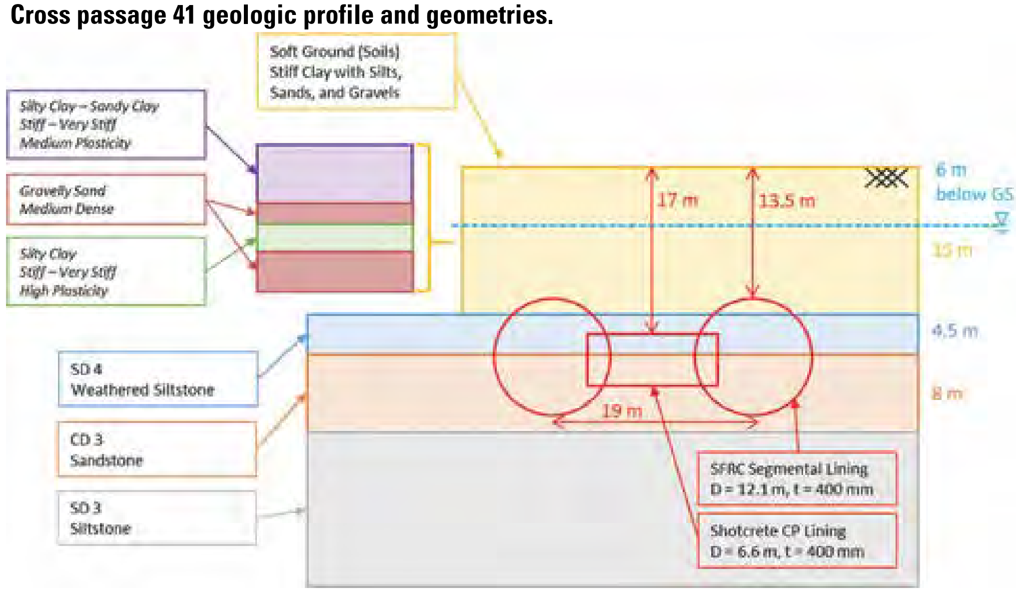
Twin bored tunnels are commonly used for a variety of road and tunnel projects throughout the world.

A major component of these twin tunnel projects is the construction of connecting cross passages that provide emergency access between tunnels and space for tunnel service equipment. Cross passages can present significant geotechnical risk and technical challenges to a project – support systems must be considered for redistributing loads around the mainline tunnel openings and supporting new loading resulting from excavation activities. Additionally, cross passages pose risks to construction schedule and cost because of their sequencing at the end of construction, so mitigation of schedule overruns can be critical. By observing field instrumentation data records from completed projects, a better understanding of the force development in each temporary structure can be achieved with indication of which structures are the most critical to support ground loads.

This article discusses the data obtained during the Brisbane Airport Link construction project, a road tunnel located in Brisbane, Australia. Strain gauge instrumentation data from the precast segmental lining and propped opening steel sets is presented with relation to the construction sequence and local geology. Interpretations and conclusions based on the observed trends are proposed, with several key mechanisms affecting the loading and unloading identified.

FIG. 1

Cross passage 41 geologic profile and geometries.



Brisbane Airport Link project overview. The Brisbane Airport Link project in Brisbane, Australia, connects central Brisbane to the airport located northeast of the downtown with more than 7 km (4 miles) of twin-bore road tunnels, two lanes each, with several caverns, interchanges and access ramps constructed along the alignment to connect to other key routes in the city. The project was executed under a public-private partnership (P3) scheme, funded and operated by the consortium BrisConnections. The main contractors were a joint venture of John Holland and Theiss, while the design was carried out by Arup and Parsons Brinckerhoff.

Construction of the tunnels was conducted using a combination of 17 roadheaders and

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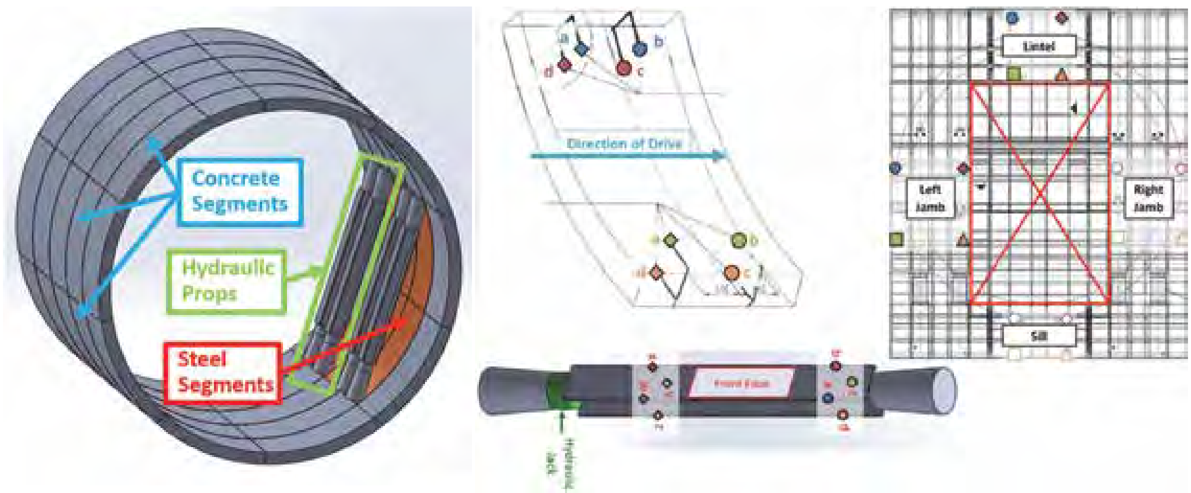
FIG. 2

Northbound tunnel, (left) instrumented components (center top) concrete segment, 8 gauges (center bottom) hydraulic prop, 8 Gauges (right) steel segments, 32 gauges, intrados and extrados at each location shown.



two 12.5-m (41-ft) double-shield Herrenknecht tunnel boring machines (TBM) (Harding & Francis, 2013). The TBMs were used in earth pressure balance- (EPB) type closed mode for the initial portion of their drive, starting at the northeast end of the alignment. Tunneling started in soft ground, weathered rock, and mixed face conditions initially, progressing to competent sedimentary rocks as the drive continued. Support was accomplished using a 12.1-m (39.8-ft) diameter steel fiber reinforced concrete (SFRC) segmental lining installed behind the TBMs in nine segments + one key arrangement. The innovative design of these segments is detailed in the paper by Harding and Francis (Harding & Francis, 2013). Ancillary roads and underground interchange caverns were constructed by sequential excavation techniques using roadheaders, accounting for nearly half of the total underground excavations.

Cross passage construction means and methods. The cross passage support in weak ground conditions, shown in a construction schematic in Fig.1, consisted of the use of steel segments around the planned opening that is two segments tall by three rings wide, and rebar-reinforced concrete segments around the opening rings. Both segment types were installed by the TBM during normal advance. Immediately prior to cross passage construction, temporary steel props were installed and hydraulically jacked, developing bearing resistance in both the lining segments and external ground mass. The load bearing props divert stress away from the opening segments and excavation face. For this article, the shallowest cross passage, XP-41, is considered because of the mixed face geologic conditions. In deeper portions of the tunnel with predominantly rock geology, the support scheme was reduced to include narrower opening sets or a lintel beam.

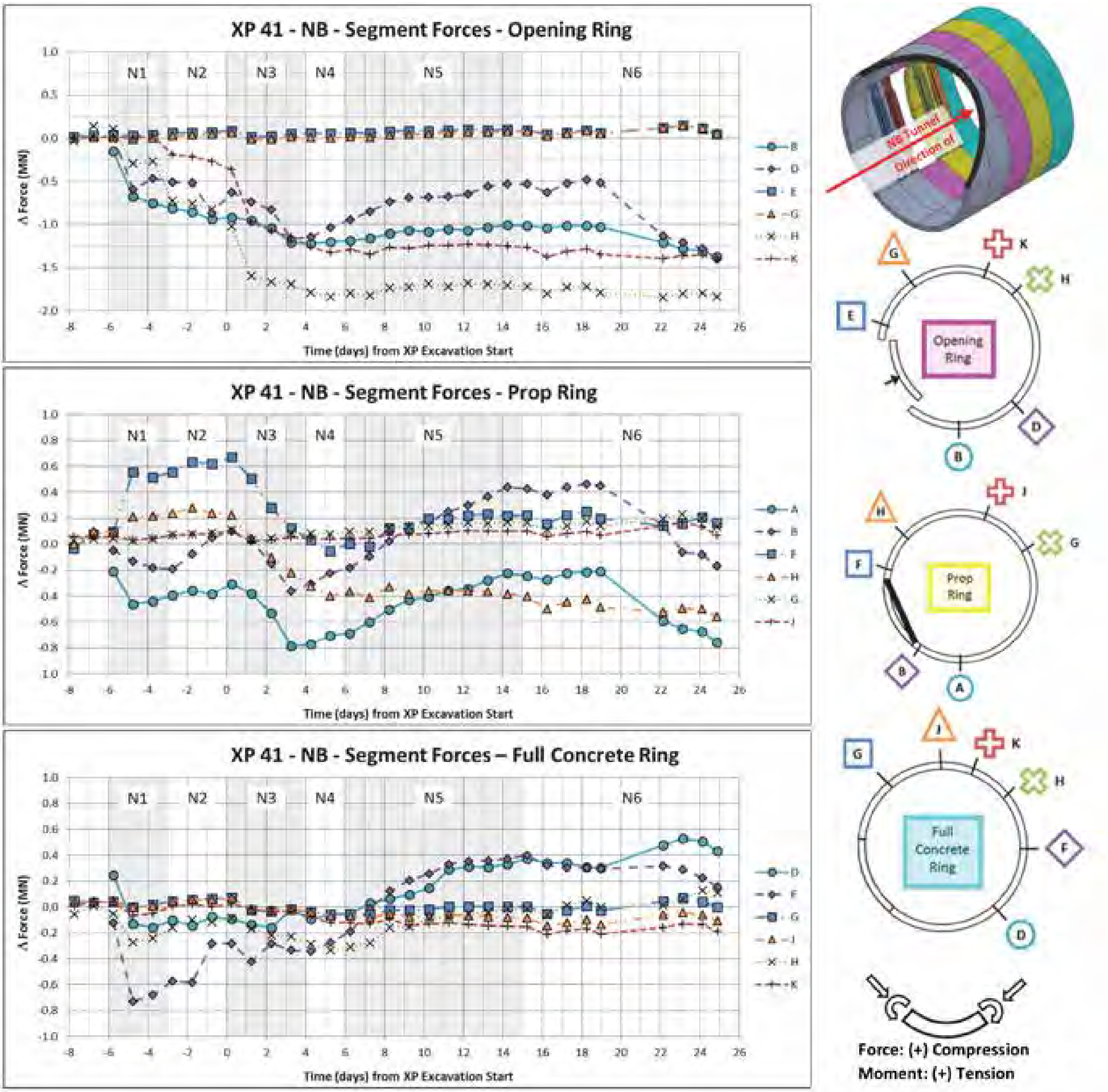
Cross passage construction activities took place several months after completion of the mainline tunnels. Pipe canopy tube installation and pre-excavation grouting were conducted in advance of construction to improve stability of the mined cross passage. Construction began with prop installation and hydraulic jacking and disassembly of the removable door segments in the steel.

Sequential excavation followed the sequence shown in Fig. 2: (a) top heading and bench excavations were performed in staggered fashion with an initial shotcrete layer on the excavation profile and face; (b) lattice girders and a finishing thickness of shotcrete were installed after the full profile was completed; (c) for continued excavations, the top heading was maintained 1 m (3.3 ft) in advance of the invert at all times to limit deformations. After excavation, waterproofing and a final cast-in-place concrete lining were installed to provide permanent support for the full design life of the structure.

Cross passage geology. To provide context for the development of forces in the structures, the geologic context must first be established. Figure 3 shows the geologic cross section, mainline tunnels, and cross passage excavation profile for XP-41. The original geologic section was constructed from boring logs in the vicinity of XP-41 and has been simplified for the purposes of this analysis. The main geologic feature of concern is the weathered siltstone layer present in the crown of the cross passage and shoulder of the mainline tunnels. This weathered rock layer has been

FIG. 3

Concrete hoop forces vs. time, averaged from 4-gauge groups at segment ends.



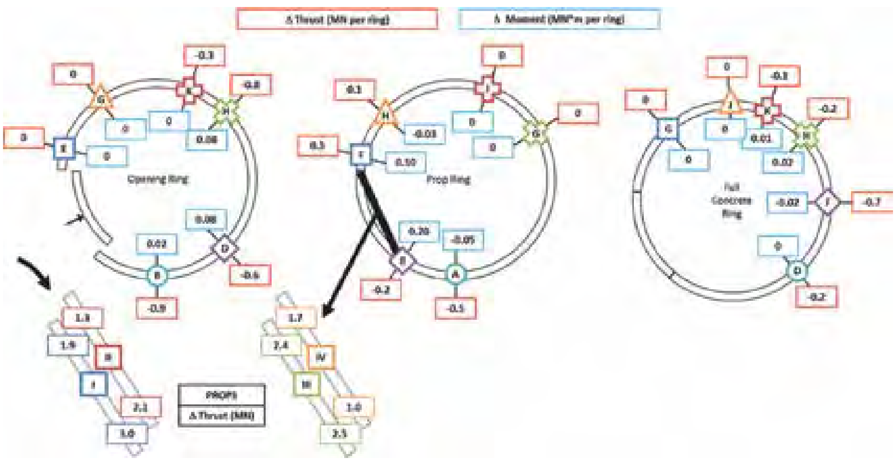
described as completely weathered in place with little to no intact structure, and was therefore expected to behave as a soft ground-type continuous material with low strength. The discontinuous interfaces between geologic layers above the cross passage were expected to interrupt the displacement and mobilization of soil arching in the ground mass, therefore full overburden conditions were assumed on the tunnel and cross passage.

Strain gauge instrumentation for opening sets

Strain gauge instrumentation was installed to monitor loading at the two shallowest cross passages, XP-40 and XP-41, because they were anticipated to experience the highest loads and least support from the surrounding ground. Vibrating wire strain gauges were installed on the steel opening segments, the steel props, and embedded within select reinforced concrete segments around the opening area. Gauge locations on

FIG. 4.

Force and moment changes for Event N1, prop jacking.



the instrumented components are shown in Fig. 4. Strain gauge frequency data was used to compute strains, accounting for initial baselining and temperature sensitivity. Standard formulae were then used to estimate stresses, forces, and moments from each group of sensors. Forces and moments were typically computed from groups of four sensors, located at the ends of each prop or segment.

Observed results. The following sections will detail the observed structural response in XP-41 and interpretation of the field measurements to understand the underlying behavior. To best visualize the field data, two methods of presentation are used – forces in a specific element over the full timeline (changes over time) and forces in all elements during a specific time interval (changes by event). This allows the reader to visualize the time and space elements of the data, relating changes between the various structures.

Concrete segment strain results over time. Figure 5 presents the development of strains over time in three rings located on the excavation start side of the cross passage (right tunnel in Figure 3). The three rings titled opening ring, prop ring, and full concrete ring include the ring centered on the steel opening set, the ring on the right side of the opening set, and the ring adjacent to the opening set steel. A small legend has been provided showing the locations of each ring and the instrumented segments within that ring.

Segments were not instrumented to the left of the opening because symmetry conditions were assumed and the instrumentation budget was limited. Each ring had three instrumented segments with a group of four gauges at each end, giving six locations in each ring where forces and moments were analyzed. These locations are shown in the legends at the right of Fig. 5, with each group of four gauges identified with the letter for the adjoining joint.

The strain gauge data was zeroed prior to the segment installation in the tunnel and was measured again after TBM passage. This gave initial geostatic values for hoop force in the range of 4 to 6 MN per segment, with moments up to 0.20 MN*m in magnitude. To clearly present the relatively small magnitude changes in the segments over time, Fig. 5 shows the forces with a reset to zero, eight days prior to the start of cross passage excavation activities (Day 8). The vertical gray bands with labels N1-N6 identify the main events impacting the development of forces in the cross passage based on the construction sequence, field notes, and observed trends in all plots. The interpretation of the above data for the concrete will be performed on an event by event basis in the following sections.

The following presentation of data discretizes the changes within each time event for both concrete and prop stresses and presents them on a spatially organized plot, to allow connections from the data to the tunnel geometry.

Event N1, installation and extension of hydraulically jacked props. The initial jacking force in the hydraulic props was targeted at 2.8 MN per prop to ensure activation of reaction forces at the ends.

Some variation of the forces is expected as locked-in forces within the jacks cause a redistribution of forces throughout the system as the elements displace and adjust to the increased load as shown in Fig. 6. Furthermore, the timing of readings and the order of prop jacking can lead to earlier props being slightly unloaded as later props attract loads. However, for a large part, the expected force from the jacking was seen by the props, with measured forces ranging from 1.3 – 3.0 MN.

The reaction against prop extension was provided by three elements – compressive reaction against the ground, compressive reaction against the segments, and a tensile reaction, or decompression, of the opening steel segments. Some of this decompression effect is also seen in the neighboring rings as well.

The opening steel and ground are the two stiffest elements (by modulus and area of reaction), so it is not surprising that the concrete sees only 0.5 MN of this increase (20 percent). Therefore, as far as the data allows, jacking engaged the prop elements to develop the intended loading in design.

It is noted that segments monitored in the invert of the tunnel near the opening set showed a decrease in hoop forces resulting from jacking. This can be attributed to the geologic condition below the tunnel invert, where the stiff sandstone provides most of the bearing resistance to the props.

Conversely, a slight increase is seen in the concrete at the top of the props since the ground does not provide as stiff of a bearing stress, so load from the propping is shared by the ground and the segments here.

Event N2, removal of temporary segments to create excavation opening. During the removal of the steel set opening segments, event N2, locked-in forces within the steel are relieved, allowing the structure to redistribute loads around the opening. The gauges on the props and near the prop abutments see the largest increase in hoop forces, up to 0.3 MN. The change in the door jamb forces is possibly due to local construction disturbance, but the contribution is expected to be similar to hold the hoop forces around the opening.

Little change is noted throughout the rest of the ring at this stage, as expected, since the same forces are applied to the tunnel, but are simply flowing around the door opening after removal. It is worth noting the lintel is working in conjunction with the props throughout the excavation to maintain loads in the segments above the opening. No change in load is seen in the opening ring segment with gauges E and G (Fig. 5) throughout construction.

Event N3, initial heading and bench excavations up to closure of shotcrete lining. This event encompasses the first four days of excavation of the cross passage, including two heading excavations and the first invert excavation. During this time, a decrease in forces is seen throughout the concrete segments and props which can be attributed to an unloading effect for horizontal ground pressures. The transmission of ground pressures between the soil and the structure requires contact at the extrados of the tunnel. Excavation activities for the cross passage remove the ground contact around the opening set thus reducing loads on the structures.

Additionally, removing the ground behind the opening set removes confinement from the back of the jambs, allowing a redistribution of bending moments and accompanying slight relaxation in force. These effects are seen most prominently in the data for the prop ring and opening ring, which are partially exposed by the excavation.

Another contributing factor is the presence of horizontal ground stresses, behaving as locked-in forces between the mainline tunnels. Initially, these horizontal forces are quite significant, particularly in the sandstone for the bench excavation which has a horizontal stress ranging from 0.8 to 1.2 times the vertical stress. Excavating the full profile of heading and bench allows the locked-in force within this geologic layer to relax between the tunnels, accompanied with slight movement of the two tunnels toward each other and a general reduction in horizontal load. After the lining is fully complete between the tunnels, the two tunnels and cross passage begin to act as a single rigid structure, which in the long-term will experience a restoration of

FIG. 5

Force and moment changes for Event N2, removal of opening segments.

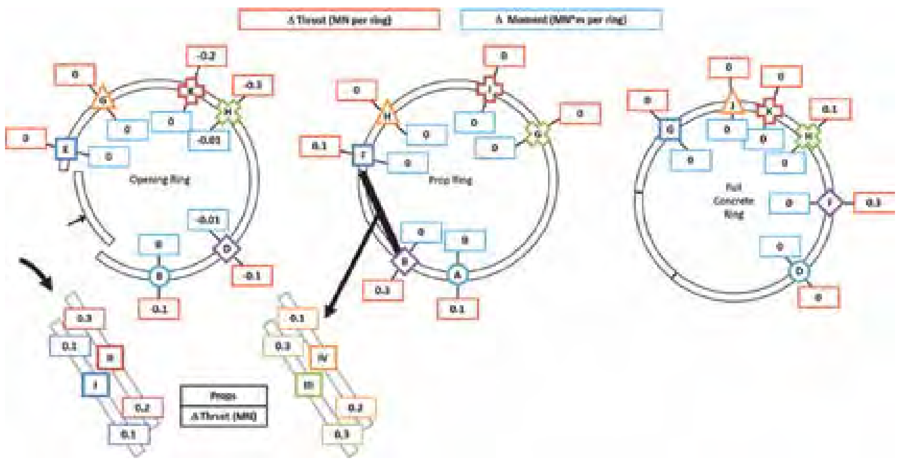


FIG. 6

Force and moment changes for Event N3, initial heading and bench excavations.

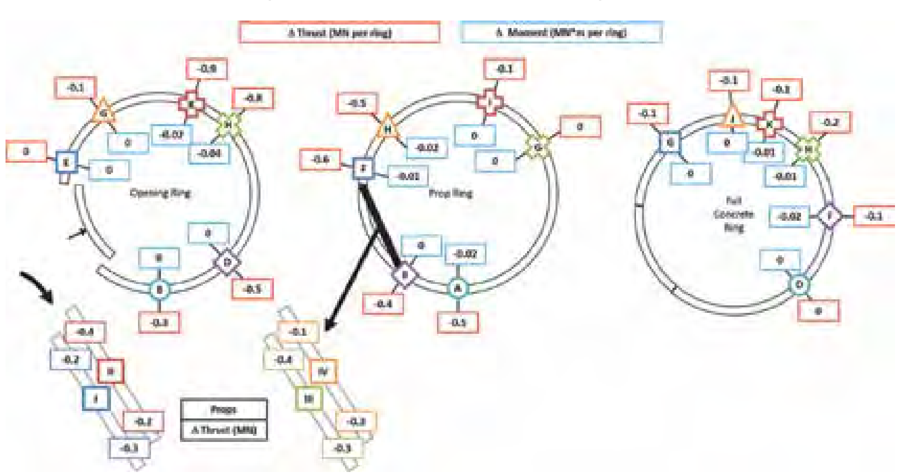
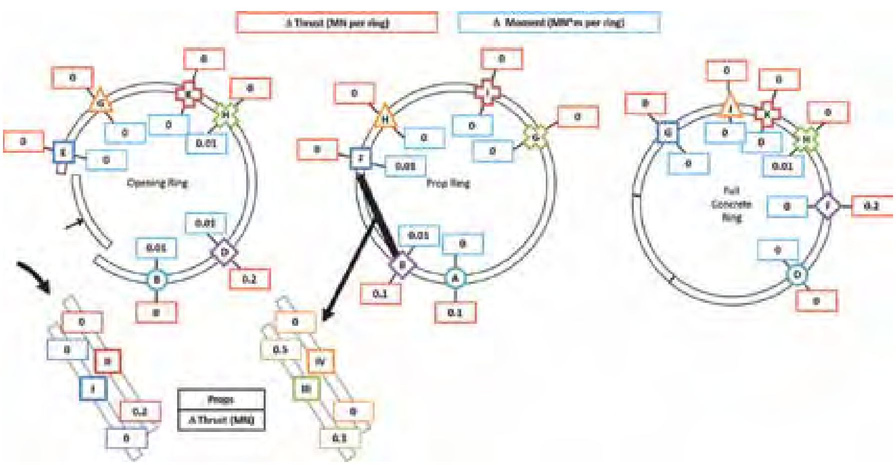


FIG. 7

Force and moment changes for Event 4, observed settlement event.



in-situ horizontal forces close to the original stress.

Event N4, cross passage ovalization and ground activation with continued advance. Following the removal of ground-structure contact behind the opening set, the state of stress in the ground has been changed. Redistribution of stresses in the ground does not occur immediately because the ground is able to support some stress change in the short term, a phenomenon usually identified empirically as standup time. After a combination of advance length and time of exposure, the ground will lose the ability to bear the change in stresses and will begin to deflect, applying load to the tunnel structures as the ground excavates. During event N4, the decreasing trend, seen prior, reverses in the segments and props as the ground stresses redistribute.

Coinciding with this ground activation and redistribution of stresses, a noticeable deflection was observed in the cross passage profile. Survey monitoring of both mainline tunnels and the cross passage was used during the excavation to warn of any excessive displacements that may affect the tunnel envelope dimensions or indicate significant ground movement that may impact worker safety.

Negligible displacements were recorded for the mainline tunnel survey targets throughout the excavation sequence of events, with changes no more than 1-2 mm from day to day, attributable to measurement noise and very minor shifts in the tunnel. However, survey data from the first heading of cross passage 41 showed vertical settlement in the crown of 1.5 cm, with 0.5 cm of vertical displacement at the springlines occurring around day four to five after the excavation start.

These displacements demonstrate an ovalization of the cross passage lining concurrent with the bench excavation of the subsequent ring. The second bench excavation overcame the ground capacity for its previous state of stress, activating the ground pressures in the vicinity, justifying the standup time principle mentioned earlier. As the shotcrete came under load, primarily vertical, it deformed to develop its structural resistance. Additionally, shotcrete is a very stiff lining material with early strength gain which often exhibits cracking and slight displacement as it develops load.

During this period of ground activation and cross passage displacement, relatively small changes are noted in the mainline tunnel structures. Slight increases in force are seen in some props and concrete segments, noting that the force increase at the top of Prop III is likely an anomaly or correction for unbalanced stresses. The data suggests that progressive excavations activate the ground to develop arching stresses and establish equilibrium with the cross passage lining rather than the mainline tunnels.

Event N5 and N6, remaining advances through completion of the lining. Event N5 and N6 were originally separated to show stress changes relating to excavation separately from stress changes after lining completion, but have been included together here for brevity since the differences in the two events were not significant. The tunnel structures see relatively small changes in force throughout the remaining excavations of the cross passage. The main observed change in forces was an increase in thrust for segments below springline of the tunnel. These changes are a rebound from a previous reduction in force during initial propping and excavation. The rebound can be attributed to the cross passage lining shotcrete providing resistance at the invert level and re-establishing the bond to the stiff sandstone in the invert, allowing a restoration of horizontal forces on the structure. It is important to note that these do not increase significantly above the initial stress – very little new loading is being seen in these structures (Fig. 5).

In the long-term, the tunnel forces are expected to reflect a restoration of in-situ vertical and horizontal stresses, with some slight reduction for arching and relaxation that will persist long-term.

However, monitoring ceased roughly two to three days after the final shotcrete layers were finished, so no information is available about future development of these stresses. Generally these forces would be carried by the permanent cast-in-place lining, so data from the temporary structures is unlikely to provide much insight.

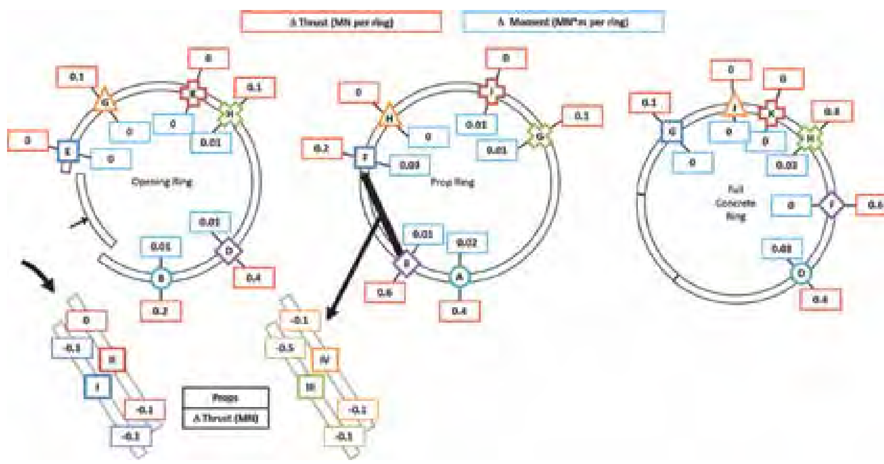
Southbound tunnel strain instrumentation. It is worth mentioning that instrumentation was conducted on the props and steel sets for the southbound tunnel as well. The data cannot be discussed in full detail within this limited format, but the general results are worth mentioning. Strain data showed a steady increase in hoop forces in the props and steel sets as the excavation progressed towards the southbound tunnel in a much more significant fashion than seen in the northbound tunnel. This suggests that excavation-induced arching behavior results in load changes ahead of and to the sides of the face rather than the structures behind the face.

However, since no concrete segments were instrumented on the southbound tunnel, this observation cannot be verified for the full ring.

Redistribution due to propping and removal of the steel sets is seen in a similar fashion to the northbound tunnels. The props once again showed that after initial jacking, they mostly act as a load path for hoop forces to bypass the opening area, as designed. One new observation available from the southbound tunnel is the stress data from the steel lintels and jambs showing significant local stress concentrations prior to propping and door disassembly. Meaningful force-moment combinations for comparison to the props could not be easily determined because of the predominance of local effects around the opening.

FIG. 8

Force and moment changes for Event N5, finishing and crown excavation.



Conclusions

Based on the presentation of data, several key mechanisms were observed throughout the construction process. First, the design intent of the hydraulically jacked props was achieved by diverting the segment hoop loading away from the opening steel and bearing into the ground. Secondly, initial advances showed a horizontal unloading effect on the mainline tunnels as ground was removed. As the excavation progressed, the existing state of stress in the ground was eventually exceeded, resulting in a redistribution of stresses and interaction with the cross passage lining. Finally, additional advances resulted in load redistribution ahead of the face and interaction with the cross passage lining, but had little effect on the tunnel structures adjacent to the initial opening.

Throughout the excavation, the magnitude of observed stresses was quite small in the concrete segments, no more than 10 percent change from the initial stress state. The prop loadings were significant, as intended, on account of the hydraulic extension and bearing against segments and ground. The steel opening sets, where data was available, showed significant stress changes, mostly resulting from local effects and redistribution of stresses in the high stiffness steel.

The use of instrumentation data on this project provided value in three areas: justification of design assumptions, monitoring of field conditions during construction, and use in research to develop understanding of ground and structure behavior. The ground-structure interaction mechanisms presented in this paper enable recommendations for future work that can improve the state of practice in the industry. The first area for further investigation is the relationship between the mainline tunnel and cross passage linings in supporting ground pressures, including aspects of relaxation effects, soil arching, and the horizontal unloading effect. Observed loading in the mainline tunnels showed relatively small changes (<10 percent), suggesting the cross passage structures (shotcrete and lattice girders) are providing the majority of the ground support. Therefore, installation of strain gauges and earth pressure sensors within the cross passage on future projects may justify a reduction in the mainline tunnel support requirements, where possible. It is noted that deflection requirements often govern the mainline supports due to tight tolerances for convergence of the segmental lining. Lastly, consistent methodology should be applied to data collection techniques in an effort to minimize the effect of human and systematic errors in the collection of readings. ■

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FEATURE ARTICLE

2016 permeation test results for grouts made with ultrafine cement

The field demonstration portion of the Underground Grouting and Ground Improvement (UG&GI) short course offered by the Colorado School of Mines was held on May 18, 2016 at Baski Inc.'s Yard in Denver, CO.

Numerous full field scale demonstrations of grouting methods and equipment were conducted under various field conditions. As part of these field tests, permeation grouting testing and demonstrations were also conducted. Various cement grout mixes were injected into 1.5-m (60-in.) tall transparent sand columns under controlled conditions (Fig. 1). The objective of the sand column permeation grouting demonstrations in the study was to show students the effects of ordinary Portland cement versus ultrafine cement on the engineering properties of the grout, and the permeation height through various types of soil stratigraphic layers in the sand columns. Similar previous demonstrations have had a specific focus on various brands of Type I-II Portland cements and ultrafine cements with a range of water cement ratios and injection pressures. More detailed information about these previous studies can be found in published proceedings (e.g. Henn et al., 2009 -2011).

Equipment and material used

The five clear plastic sand columns were 191 mm (7.5 in.) inside diameter and 1,524 mm (60 in.) tall. Each sand column had a 19 mm (0.75 in.) diameter hole drilled at the base (bottom) of the blind flange for injection of the grout. A perforated plate and/or screen at the base of the sand columns helped to prevent sand from plugging injection port. A ChemGrout grout plant was used for the demonstration consisting of 0.36 m^3 (97 gal) high shear (colloidal) tank mixer, a 0.36 m^3 (97 gal) agitator tank and a progressive helical cavity pump with maximum output capacity of 77 L/min (20 gpm) at a maximum discharge pressure of 265 psi (18 bar) (Fig. 2). A simple grout header arrangement consisting of control valves, pressure gauges, flow meter, grout delivery and return line, and a short injection line was also custom built. Also used were infra-red thermometers to measure the temperatures of the grout mix batches, CRD and marsh funnels to measure viscosity, baroid mud balance to measure specific gravity, and a digital scale to measure weights. The grout materials used were Holkim Portand cement (Type I-II), Nippon Steel Sumikin superfine cement and U.S. grout ultrafine cement.

Testing procedure

Five separate batches of ordinary Portland cement (OPC) grout and ultrafine cement grout from Holkim, Nippon Steel and US grout were mixed up using various water: cement ratios. The first batch consisted of OPC at a water cement ratio of 1:1. For the next batches, ultrafine cements were used and the water content was increased by 0.5 each time for the next three ultrafine mixes. Inspection of each new batch of grout mix was conducted and results recorded. The information recorded included quantities of cement

FIG. 1

Transparent sand columns.

Rennie Kaunda, Raymond Henn, Alex Peretiatkol, Ali Nazem, Fei Wang and Zoheir Khademian

Raymond Henn, member UCA of SME, is owner RW Henn, LLC and professor Colorado School of Mines and **Rennie Kaunda, Ali Nazem, Zoheir Khademian,** members UCA of SME, **Alex Peretiakol** and **Fei Wang** are assistant professor, student, student, graduate student and graduate student, respectively, at the Colorado School of Mines, email rhenn@rwhenn.com.

and water added to the mixer, the mixing times, admixture type and the vertical distance travel time in each column. Prior to grout injection through each column, tests and measurements were conducted on each grout batch for temperature, specific gravity and marsh funnel viscosity. The five columns were filled up in the same fashion: with pea gravel at the bottom and grading finer upward (i.e. gravel, course sand, med-sand, fine sand, and clay). Dye or food coloring was added to each grout batch mix. The different grout mixtures were injected at equal injection pressure (about 10 psi) into the bases of each of the five sand columns, allowing the grout to permeate upwards through the sand. The penetration height of the grout was measured every minute, up to about 30 minutes. At end of injection the final height of the injected grout and the height of bleed water were measured. The results of the tests are provided in Table 1 and Table 2.

Discussion of test results

Five clear plastic columns were filled the same way bottom up: pea gravel – 0.3 m (1 ft), coarse sand (#30) – 0.3 m (1 ft), medium sand (#50) – 0.3 m (1 ft), fine sand (#70) - 0.3 m (1 ft), and bentonite -0.15 m (-0.5 ft), and injected with different grout mixtures. The final grout permeation height using ultrafine cements was greater than using OPC in all cases, especially through the relatively finer sands. The ultrafine cement grouts made it to the top of the columns at all the different water: cement ratios used in the batch. In four of the five test cases (excluding the OPC batch), the injected grout pushed up (jacked) the sand strata up the column causing the cap to lift upward a few to several inches. The push-up could have occurred as a result of the injection pressure (10 psi), although this was relatively optimum compared to the injection pressures used in the past ranging from 5 psi (0.3 bar) to 10 psi (0.7 bar). A second explanation could be due to the dry conditions of the Gravel-sand-clay strata inside the columns; previously moist sand columns have been used with no gradation.

FIG. 2

Agitator tank and progressive helical cavity pump.

TABLE 1

Test number	Supplier	Name of product	W:C Ratio	Cement lbs (kg)	Water labs (kg)	Water gal (L)	Plasticizer %/ml	Mixing time/sec
T-1	Holkim	Portland cement	1	185.2 (84)	185.2 (84)	22.2 (84)	6000 (ml)	180
T-2	Nippon Steel	Sumikin Cement (Superfine)	1	132 (59.9)	132 (59.9)	15.8 (59.8)	600 (mL)	185
T-3	Nippon Steel	Sumikin Cement (Superfine)	1.5	88 (39.9)	132 (59.9)	15.8 (59.8)	0.4 (%)	182
T-4	US Grout	Ultrafine	2	88 (39.9)	176 (79.8)	21.2 (79.9)	0.4 (%)	187
T-5	Nippon Steel	Sumikin Cement (Superfine)	2.5	88 (39.9)	220 (99.8)	26.4 (99.9)	400 (mL)	181

TABLE 1

Test number	Ambient air temp F° (C°)	Grout temp F° (C°)	Specific gravity	Unit weight pcf (kg/m^3)	API (13-B2) marsh funnel viscosity sec/946cc	Duration injecting to column sec	Injection pressure psi (bar)	Final grout water height in column in. (mm)
T-1: Comment:	68 (20) None	72 (22.2)				300	10 (0.7)	0.2 (5)
T-2 Comment:	64 (17.8) Grout pushed up sand lay-ers after 10 mins caus-ing cap to lift up a few inches	75 (23.9)	1.5	93.6 (1,500)	27.7	540	10 (0.7)	17.5 (445)
T-3 Comment:	64 (17.8) Grout pushed up sand layers after 4 mins causing cap to lift up a few inches	74 (23.3)	1.4	87.4 (1,400)	26.3	180	10 (0.7)	18.8 (478)
T-4 Comment:	64 (17.8) Grout pushed up sand layers after 2 mins causing cap to lift up	75 (23.9)	1.2	74.9 (1200)	26.3	90	10 (0.7)	18.3 (465)
T-5 Comment:	64 (17.8) Grout pushed up sand layers after 5 mins causing cap to lift up a few inches	70 (21.1)	1.2	74.9 (1200)	25.1	240	10 (0.7)	26.3 (668)

However, during the field demonstrations in 2010, injected grout caused the sand and cap to move upward a few inches in two of the tests.

Acknowledgments

The authors thank Hank Baski and Baski Inc's yard for the use of their facilities. Thank you to Joe Schatz of ChemGrout for providing the sand columns, grout header and supervising the batching of the grouts. Thank you to Bill Warfield for pre demo day coordination and transportation of materials. Thank you to Bradley Meyer and Rick Bearce from CSM who helped out with the logistics. And last but not least, a big thank you to Brian Jeppsen of Hess Pumice Products and Brad Crenshaw of Ground Engineering Contractors for running the marsh funnel and mud balance tests. ■

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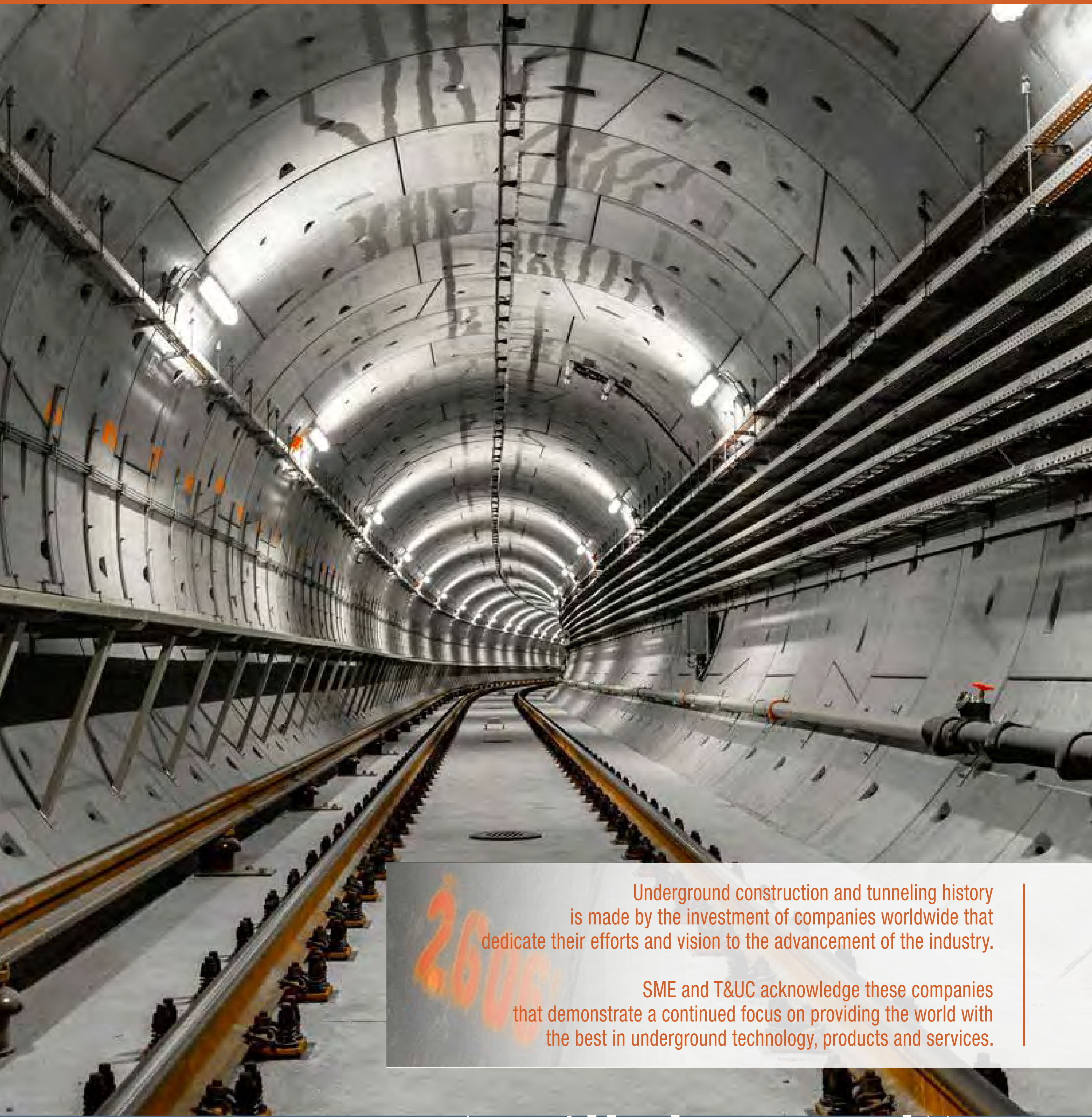

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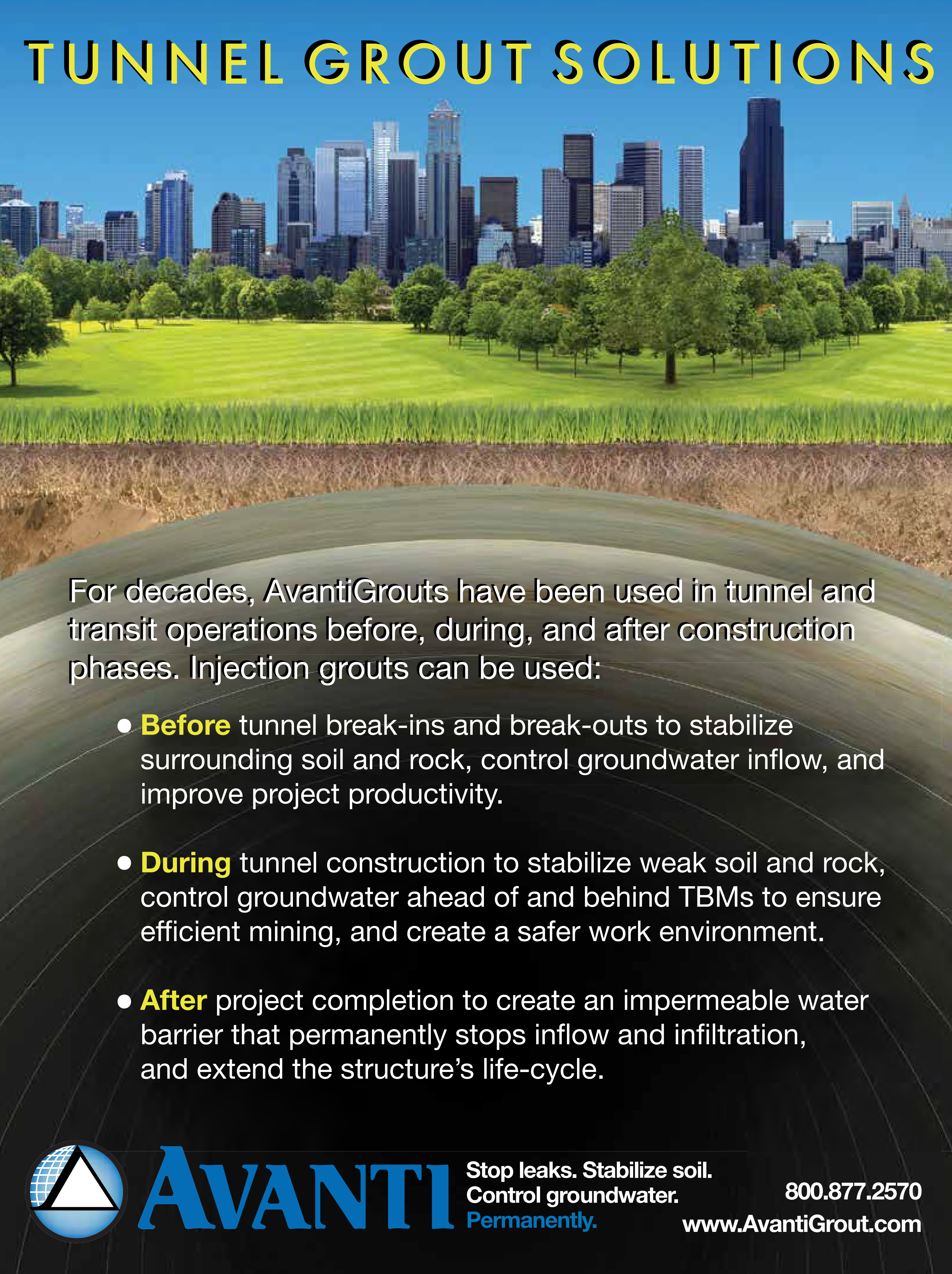
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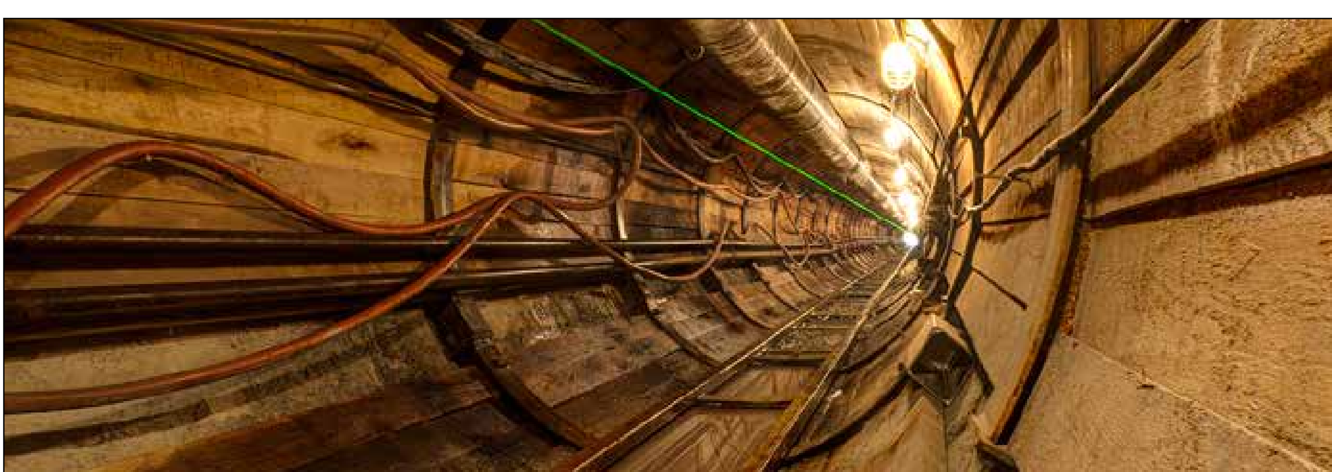

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Brightwater Conveyance System

Los Angeles, CA
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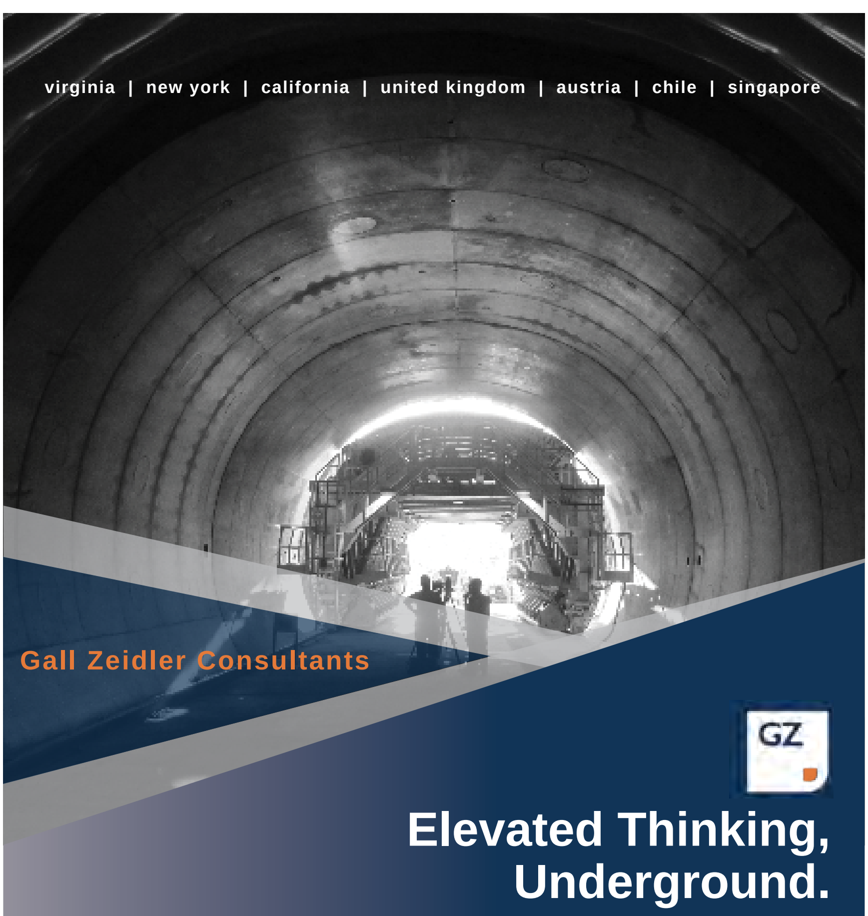

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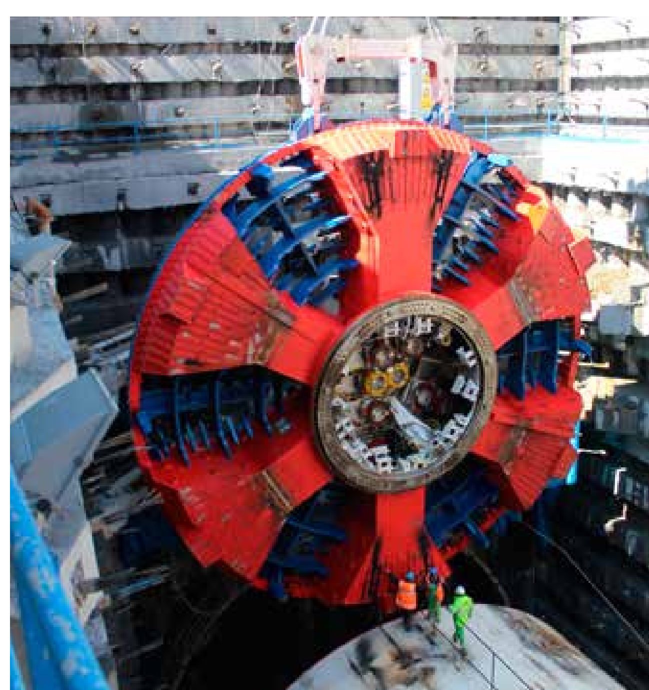

TOP CLOCKWISE: Istanbul Strait Road Tunnel Crossing *Istanbul, Turkey* | Crenshaw/LAX Transit Corridor *Los Angeles, California*
Tom Lantos' Tunnels *California* | Alaskan Way Tunnel *Seattle, Washington*

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JENNMAR Civil is dedicated to providing products and services to the Civil Construction and Tunneling industries. Products include various types of rock support bolts, anchoring systems and resins to support tunneling, geotechnical, foundation and earth retention projects.

J-LOK

J-LOK manufactures state-of-the-art resin anchorage systems that are designed to complement JENNMAR products and provide an optimum bolt and resin system. J-LOK equipment is among the most technologically advanced in the resin industry.

JENNCHEM

JENNCHEM designs and delivers chemical roof support, rock stabilization and ventilation sealing products to the mining and underground construction industries.

KMS (Keystone Mining Services)

KMS (Keystone Mining Services) is JENNMAR's engineering affiliate that provides advanced engineering services such as structural analysis, numerical and 3-D modeling, as well as conducting research and development of new products.

JENNMAR Specialty Products

JENNMAR Specialty Products is a full-scale steel fabricator specializing in roll-forming coil, sheet and structural beams to provide quality arch and corrugated products. In conjunction with KMS, we can also custom design and fabricate products for a variety of applications.

JM Steel

JM Steel's steel processing facility, located on Nucor Steel's industrial campus near Charleston, SC, has the processing capability and extensive inventory to provide a variety of flat rolled steel products including master coils, slit coils, blanks, beams, sheets, flat bars and panels.

JENNMAR McSweeney

JENNMAR McSweeney is a leading manufacturer of forged drill steel products for the underground mining and civil construction industries, along with a complete line of bolt wrenches, socket accessories, chucks, augers, and other related products.

CSA (Compliance Staffing Agency)

CSA is an energy industry staffing service that provides trained, experienced, drug-screened personnel and can supplement an existing workforce during peak work periods or act as a screening service for potential new hires.

MARJENN Trucking

MARJENN Trucking provides trucking services throughout the eastern and mid-western U.S. to transport raw materials, supplies and finished products between JENNMAR plants, suppliers and customers.

JENNMAR continues to grow, but our focus is always on the customer. We feel it is essential to develop a close working relationship with every customer to understand their unique challenges and ensure superior customer service. JENNMAR's commitment to the customer is guided by three words; SAFETY, SERVICE and INNOVATION that form the foundation and identity of our business. It's who we are.

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Moretrench

The challenges inherent in tunneling operations are well known. What is perhaps not so well known is that only one geotechnical contracting company has the in-house range of ground improvement tools to resolve even the most complex subsurface conditions. That company is Moretrench. Whether the issues are known in advance or occur unexpectedly, call Moretrench because when it comes to the complexities of underground construction, no one has seen more.

Delivering liquid nitrogen to the Port Mann off-shore working platform.

Port Mann Water Main: Ground Freezing

Mining of the new, 3,280-ft long Port Mann Water Main was well underway deep below the Fraser River in Vancouver, British Columbia, when an unanticipated mechanical failure occurred in the cutter head, halting mining operations. When initial more conventional approaches to allow access for repair were ruled out, the tunneling contractor contacted Moretrench. Moretrench developed a liquid nitrogen ground freezing solution that would not only allow safe access for inspection and repair but could also be implemented quickly. The remote TBM location, 160 ft below river mud line and 650 feet from the exit shaft, meant that all equipment and materials, including liquid nitrogen storage tanks, had to be ferried to the pile-supported work platform. Pinpoint drilling for freeze pipe installation was critical to ensure freeze build up exactly as designed. After just 12 days of freezing, the freeze was sufficiently formed to allow safe entry into the cutter head for repairs to begin.

High mobility grouting of karstic rock enabled dry excavation of the OARS CSO shafts.

OARS Relief Sewer Phase 2 Shafts: High Mobility Grouting

Drill and blast installation of three deep shafts through highly variable karstic conditions was the challenge facing the design and construction teams for Phase 2 of the CSO project in Columbus, OH. The shafts extended through shale underlain by three distinct strata of karstic limestone. With the water table 20 ft below the surface, and the high hydraulic conductivity of the rock evident from pumping tests, it was estimated that inflows of thousands of gallons per minute could be anticipated during shaft excavation under hydrostatic head of up to 150 ft. Pre-grouting was therefore required. A Moretrench-designed alternate to the original in-shaft staged grouting plan allowed all grouting to be accomplished around the shaft perimeter from the surface. A suite of four, balanced-stable grouts developed by Moretrench catered to the highly variable subsurface conditions. With grouting complete, excavation proceeded with only minimal shaft inflow.

Jet grout cut-off for installation of the Mulry Square vent plant.

Mulry Square Vent Plant: Jet Grouting:

The Mulry Square emergency vent plant is designed to serve a portion of both the 8th and 7th Avenue subway lines in Manhattan, New York. With offsite groundwater drawdown during construction prohibited, a perimeter cut-off was required. This was designed as secant pile walls, with jet grouting specified for closure where the vent plant penetrated the wall of the subway tunnel. Groundwater modeling by Moretrench demonstrated that the jet grouting would need to extend only to a minimum depth of 53 ft to achieve cut-off, rather than the 100 ft originally anticipated, reducing the quantity of secant piling and jet grouting required. Subsequent groundwater monitoring during excavation to full depth within the secant pile/jet grout cut-off structure confirmed the accuracy of the groundwater modelling and offsite drawdown did not exceed the specified limits.

For more on these and other tunneling projects, visit us at:
www.moretrench.com.


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Grouting
Ground Freezing

Kiewit

As a construction, mining and engineering leader, Kiewit is a FORTUNE 500 company with 2015 revenues of $9 billion. Kiewit, through its operating companies, brings a wealth of diverse resources and a track record for delivering the highest quality results — on budget and on schedule. Kiewit's size and experience provides the stability, predictability and know-how our clients and partners expect — and the flexibility and overall best value they deserve.

Kiewit has been constructing underground facilities for over 50 years, offering some of the most highly skilled and experienced teams in the industry. We have completed more than 100 underground related projects totaling more than $1 billion. Our tunneling portfolio includes projects related to transportation, water / wastewater facilities, power, mining, and telecommunications. In addition, Kiewit has the resources to construct cut-off walls, structural slurry walls, drilled shafts and ground improvement. We perform these operations with our fleet of specialty equipment and the management resources of one of the top builders in North America. Through the use of cutting-edge technology, industry-leading safety performance and a wide range of capabilities, we offer our clients an innovative, one-stop shop for all their tunneling needs.

Kiewit Infrastructure Co.
302 South 36th St., Suite 400
Omaha, NE 68131
402-346-8535

PKS KIEWIT SINCE 1884 Kiewit

Our projects range from fast-track mining jobs to a $1 billion undersea rail tunnel. No project is too large or small when it comes to meeting our clients' needs. Our clients in these markets have come to expect the industry's safest work environments, the highest-quality delivery and superior compliance with requirements of all types. Behind it all are the core values that have shaped how we manage our business — for our clients and other key constituents.


Kiewit

Brokk Inc.

Brokk Inc. has been the world's leading manufacturer of remote-controlled demolition machines and attachments for over 40 years. Through continuous innovation in engineering and design, Brokk is able to offer unique solutions to multiple industries worldwide, including construction, demolition, mining and tunneling, cement and process, nuclear and other specialty applications.

The new Brokk 110 demolition machine delivers 15 percent more power than its predecessor, the Brokk 100, without sacrificing the compact size and versatility for which the company's machines are known.

Brokk recently introduced the new Brokk 110 remote-controlled demolition machine. The electric-powered unit features increased demolition power over its predecessor, the Brokk 100, and includes the all-new Brokk SmartPower™ electrical system. The machine's improvements increase the reliability and versatility for Brokk customers working on harsh jobsites in industries such as construction, metal processing, mining and nuclear.

The new machine features a 10-foot (3-meter) reach and weighs 2,183 pounds (990 kilograms). It delivers 15 percent more power than the older Brokk 100 and 50 percent more than its predecessor, the popular Brokk 90 (discontinued in 2011) while retaining its compact design, making it ideal in restricted spaces and on weak floors.

The Brokk 110 includes Brokk SmartPower, the company's all-new electrical system, which is also available on the new Brokk 120 Diesel and Brokk 280. The intelligent system incorporates hardened components and fewer moving parts than its predecessor. Brokk SmartPower optimizes performance based on a number of factors, including power supply quality and ambient temperature. The system can sense when a power supply is poor or faulty, making it suitable for generators or unreliable power supplies.

In addition to improvements to its overall power and electrical systems, the Brokk 110 also features upgraded durability. This includes hardened parts, LED headlight protection, reinforced corners and a new steel gray color coating in strategic areas to add additional resistance to dirt and scratches.

The Brokk 110 features hardened parts, LED headlight protection, reinforced corners and a new steel gray color coating in strategic areas to add additional resistance to dirt and scratches.

The Brokk 110 is compatible with the same wide range of attachments available for the Brokk 100 that it replaces, including breakers, crushers, grapples, rock drills and shears. At 31-inches wide, the compact machine and its attachments fit easily through standard doors and inside passenger elevators. With its low floor load, the Brokk 110 is able to maneuver in otherwise inaccessible areas, such as stairwells or elevators. Its compact size is ideal for a variety of applications, from top-down demolition and interior strip-outs to selective concrete removal.

For more information: Brokk Inc., 1144 Village Way, Monroe, WA 98272; 800-621-7856; info@brokkinc.com; www.brokk.com; Facebook and Twitter: @BrokkUSA; LinkedIn: Brokk Inc.; YouTube: BrokkIncUSA.

The Brokk 110 comes equipped with the new Brokk SmartPower™ electrical system and features a rugged design made to withstand even the harshest jobsites.

Premier Pipe Systems Manufacturer for Over 90 Years

Since 1925, Naylor Pipe Company has been the premier manufacturer of Spiralweld pipe systems.

Naylor Spiralweld is available in diameters from 4" through 96" and wall thickness from 14 Ga. through 1/2" wall. The Spiralweld pipe is complemented with all types of fittings, fabrications to specification, and joint connections, including the exclusive Naylor Wedgelock Coupling, to complete your pipe system.

Naylor Spiral Buttweld pipe features two welds along the spiral seam. This creates a pipe structure in which the weld is as strong or stronger than the parent metal.

The Naylor manufacturing process creates a pipe that maintains an accurate diameter throughout its length. The uniformity of the pipe ends speed connection, whether mechanically coupled or welded.

Uniform wall thickness is assured because tolerances of steel strip are governed by the standards established by the American Iron and Steel Institute. In addition, the pipe is furnished in any required length with a cutting tolerance of plus or minus 1/8".
In addition to carbon steel, spiralweld pipe can be formed from many steel grades, including abrasion resistant, weathering (A-588) and stainless.

Every length of Naylor Pipe is inspected and where required hydrostatically tested to applicable ASTM specifications. The pipe is available in lighter weights than other pipe making it possible

to save money, not only on initial cost, but also in transportation, handling and installation. By sizing the diameter of the pipe to the exact requirements, with exact lengths and factory-sized ends, the greatest economies can be realized.

Quotations are immediately available on inquiry.

Naylor Pipe Company
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Email: sales@naylorpipe.com
www.naylorpipe.com

Antraquip Corporation

Antraquip Corp. has established itself as a leading designer, manufacturer and supplier of roadheaders, hydraulic rock grinders (roadheader attachments), shaft sinkers, specialty tracked machines with a variety of boom options, and tunnel support systems. The newest addition to the Antraquip product line are diamond tipped rock saw attachments for excavators designed to cut hard rock and reinforced concrete for specialty applications. Antraquip machines, built to the highest technical standards, are being used all over the world in a variety of civil engineering and mining projects.

Antraquip offers not only standard roadheaders in the 12 to 75 ton weight classes but is proud to offer project oriented engineering solutions. Some of the recent projects have included AQM roadheaders equipped with customized drilling attachments and fully automated remote control operation. Antraquip also provides various tunnel support products including lattice girders, steel sets, and arch canopy systems which they have supplied to some of the highest profile projects in North America in recent years.

In addition to offering project consultations, innovative rock cutting solutions and tunnel support systems, Antraquip recognizes the importance of after sales service. Their commitment to offering the best service and technical support is carried out by highly proficient and experienced service technicians and reinforced with the largest roadheader parts inventory in North America. Innovation, reliablility and experience offered by Antraquip, continues to make them your reliable partner for any tunnel or mining project.

Antraquip Corporation
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Email: info@antraquip.net
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CDM Smith

CDM Smith provides lasting and integrated solutions in water, environment, transportation, energy and facilities to public and private clients worldwide. As a full-service engineering and construction firm, we deliver exceptional client service, quality results and enduring value across the entire project life cycle.

CDM Smith's underground construction staff includes geotechnical, structural, and civil engineers and geologists located worldwide. Our staff has extensive experience in providing the full range of tunnel and geotechnical related services. Our tunnel related work includes planning, feasibility and design, including both 2D and 3D FEM analyses. We offer construction services including construction and program management, inspection and geotechnical instrumentation monitoring and interpretation for soft ground and rock tunnels. Design and construction includes all types of ground modifications including ground freezing, grouting, and dewatering.

Our field equipment includes geotechnical instrumentation and construction data acquisition equipment. Our field personnel are NICET, OSHA and NRC certified. CDM Smith's tunnel services include:

- Shaft Design: Ground Freezing, Slurry Wall and Secant Pile Wall
- Conventional Soft Ground and Rock Tunnel Design, Microtunneling, Pipe Jacking and Directional Drilling
- Evaluation and Rehabilitation of Existing Tunnels
- Ground Investigation, Testing and Evaluations
- Groundwater Control System Design

CDM Smith
www.cdmsmith.com

CDM Smith

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Mott MacDonald

Tunnel engineering is one of Mott MacDonald's core services. For a wide-range of public and private clients, we have engineered transportation tunnel solutions for roadway, passenger rail, freight rail, subway, pedestrian, cable and communications projects. Our expertise spans a broad-range of capabilities from the planning and implementation of new facilities to the inspection and rehabilitation of existing facilities.

Our involvement in tunneling began more than a century ago, dating back to our founders' involvement with London's underground road and rail systems in 1902, and Toronto's subway system in 1954. Our association with these clients continues today – a testimony to the trust, confidence, and professional relationship we build with our clients and to the quality of our work.

With more than 75 offices throughout North America, Mott MacDonald offers a full-range of services to handle any size project – from a small inspection assignment to world-class, multi-billion-dollar transit programs.

Our goal is to deliver client projects in an environmentally responsible manner, with value-added design and construction methods – minimizing programmatic risk along the way.

Agru America

AgruFlex® Tunnel Liner

Whether used in blast and bored or conventional tunnel constructions, AgruFlex® Tunnel Liner protects concrete tunnel structures against the infiltration of water, aggressive soils and root penetration. A very low density polyethylene (VLDPE), AgruFlex® Tunnel Liner combines flexibility with tensile properties, chemical resistance and long-term performance. Due to its superior water resistance, AgruFlex® reduces the maintenance work needed to repair water spots, dripstones from lime diffusion and external concrete corrosion.

Because VDLPE contains no volatile plastizicers, the AgruFlex® keeps its mechanical properties – ensuring tight construction for the life of the tunnel. AgruFlex® is easy to install with good weldability. It emits zero toxic fumes in case of fire. AgruFlex® combines a black base layer with a bright signal layer and can be used with geotextile, HDPE or LLDPE liners for cut and cover tunnel constructions.

About Agru America, Inc.

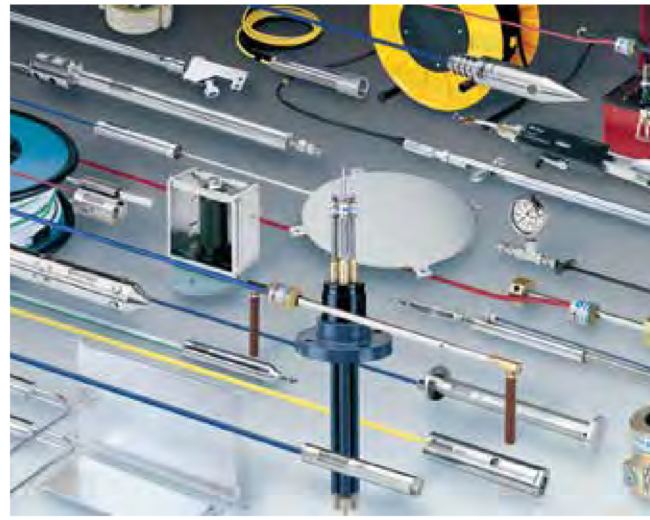
Since 1988, Georgetown, SC–based Agru America, Inc. has been the world's leading manufacturer of flat die extrusion geomembranes, geonets, geocomposites, geotextiles, GCLs, concrete protective liners and tunnel liners. The company also supplies vertical barrier systems and piping systems for the U.S. and international civil/environmental markets. In addition to AgruFlex®, Agru's state-of-the-art products include Agru Smooth Liner® / MicroSpike® (structured textured products), Super Gripnet®, and Drain Liner® in both LLDPE and HDPE. Agru America is part of Alois Gruber GmbH, an Austrian family-owned business since 1948 with production facilities in Austria, the U.S., Germany, China and India, and distribution in over 80 countries worldwide.

Geokon, Incorporated

Geokon, Incorporated, is a 35 year-old company based in Lebanon, New Hampshire, USA. It operates on a worldwide basis through a network of over 45 agencies for the manufacture and sale of geotechnical instruments. Founded in 1979, Geokon currently has over 100 experienced employees, many of whom have been with the company for over 25 years. Geokon, Inc. has emerged as The World Leader in Vibrating Wire Technology™ and one of the major global instrumentation companies due to our high-quality products, responsive customer service and industry-leading designs.

In addition to almost all major cities in the USA, our instruments have been used in tunnels and subway systems around the world, including those found in Seoul, Taipei, Guangzhou, Istanbul, Hong Kong, Singapore, London and the Channel Tunnel.

Tunnel-specific instruments include NATM-style concrete pressure cells for monitoring stresses in shotcrete linings; convergence meters and tape extensometers to measure tunnel closures; multiple-point borehole extensometers and instrumented rockbolts to monitor the stability of the surrounding ground; piezometers to monitor ground water pressures and displacement gages to measure movements across cracks and joints. Dataloggers are used to take readings at programmed intervals and transmit real-time data (and any triggered alarm signals) to local stations or to remote readout locations using web-based software.



Geokon's experienced staff is at your disposal to assist in instrument design, selection and installation. For more information please visit www.geokon.com, e-mail us at info@geokon.com or call 1-603-448-1562 and speak to a sales representative.

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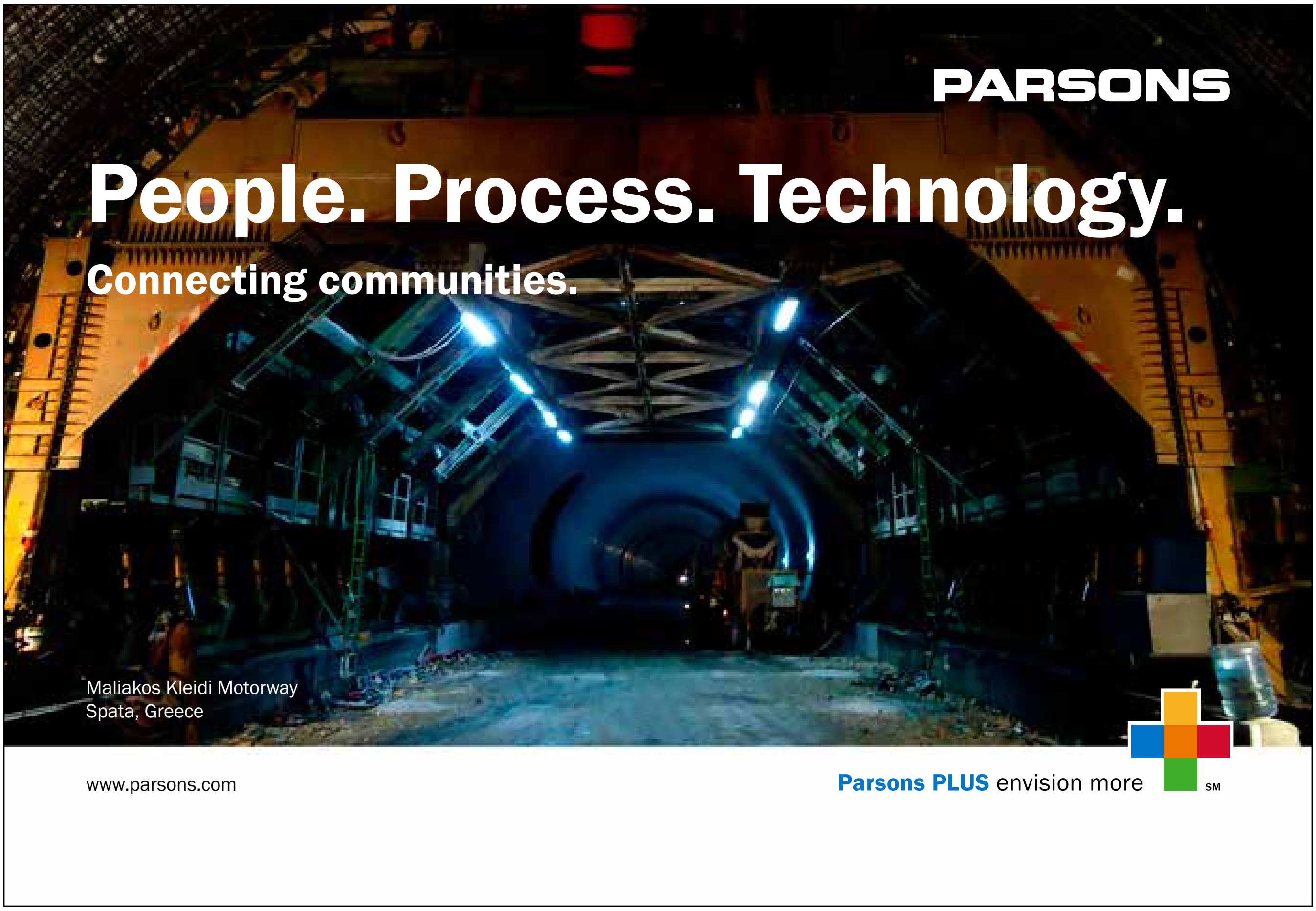
Connecting infrastructure across the globe.

Industry leaders. Delivering innovative solutions.

Founded in 1944, Parsons—an engineering, construction, technical, and professional services firm—is a leader in many diverse markets, focusing on infrastructure, industrial, federal, and construction. We deliver design/design-build, program/construction management, and other professional services packaged in innovative alternative delivery methods to government agencies and private industrial customers worldwide.

Parsons has successfully delivered some of the largest and most complex tunneling and underground construction projects in the world. From planning and design through construction management and operations, we provide a complete range of services for water, wastewater, and transportation tunnels. Whether your project involves soft ground, rock, or mixed-faced conditions, our dedicated staff of more than 100 tunnel professionals have the experience and skills to manage the risks and deliver safe, economical and innovative solutions. Our recent award-winning projects, such as Lake Mead Intake No. 3 and the Sheikh Zayed Road and Tunnel, demonstrate Parsons' position as an industry leader and our dedication to delivering challenging projects. Parsons knows and understands the challenges associated with tunnels and underground structures. Our depth and range of expertise coupled with our innovative and sustainable solutions, helps us to meet the needs of our customers today and in the future. Our expertise is illustrated through our commitment to our core values: safety, quality, integrity, diversity, innovation and sustainability and through our many award-winning projects. Learn more at www.parsons.com.

Learn more at www.parsons.com.



Schauenburg

We are pleased to announce the formation of a cooperative Business Alliance between Schauenburg Flexadux Corp (www.schauenburg.us) and Protan AS (www.protan.com) to better serve the Tunnelling and Mining across the United States.

This cooperative approach involves combining the strengths of Protan's years of manufacturing and supply of top quality Tunnel Ventilation PVC Ducting and Technical solutions to the global mining and tunnelling industries with Schauenburg Flexadux's 40 plus years of local US Manufacturing, Supply and customer service to these industries.

The major benefits of this Business Alliance is to combine the 60 plus years of Protan experience in designing and supplying lower friction Ventilation Technology with the dedicated local commitment of Schauenburg Flexadux to supply fast deliveries to meet our customers production requirements.

The major benefits to our valued end-user clients are:

1. Combination of Recognized World Class Ventilation Technology with dedicated local manufacturing, sales, service, and support.
2. Fast response time to design and manufacture of specialty products.
3. Elimination of supply logistics related to long delivery concerns, customs and other import administrative costs.
4. Addresses the fluctuating currency exchange rates.
5. Competitive pricing to address the realities of the US Market Demands.

We look forward to working jointly together with you to provide quality ventilation products and services to assist you to be a profitable leader in the United States mining and tunnelling business.

Please feel free to contact us at any time with any questions.

John Kelleher, P.Eng.
President
Schauenburg Flexadux Corp.

Mark Andersen, P.Eng.
Director N. America
Protan AS

ABC Industries, Inc.

For over 90 years, ABC Industries continues to be a leading supplier of high quality, customized ducting solutions in many of the largest mine, tunnel and underground construction operations worldwide. ABC's complete line of layflat blower tubing, ducting, brattice, fly pads, blast curtains, fans and accessories offer a complete ventilation solution for underground professionals. As tunneling and underground construction continue to evolve, ABC proactively collaborates with industry professionals to engineer unique, premium ventilation products exceeding the needs of the industry.

A new innovative addition to ABC's arsenal, RigiVent™ is a flexible, interlocking ducting solution for positive pressure applications requiring minimal storage and ease of handling. Similar to RigiDuct®, RigiVent™ is constructed from filament wound fiberglass rovings and reinforced with polyester fibers for added strength and resiliency.

To see more innovative products, please visit us at www.abc-industries.net.

Northwest Laborers-Employers Training Trust

The Northwest Laborers-Employers Training Trust's Safety and Hazard Awareness for Tunnels (SHAFT) curriculum focuses on providing comprehensive tunnel safety, rail, and utilities instruction for both new and experienced tunnel professionals. The courses, developed by NWLETT with input from industry experts and stakeholders, blend interactive use of materials and real-world mockups with classroom instruction and discussion to provide a unique educational experience. The training facility, located in Elma, Washington, features a TBM mockup, working loci, and access to 1,400' of 12' diameter tunnel.

Northwest Laborers-Employers Training Trust
+1 (800) 240-9112   www.nwlett.org

Brookville

BROOKVILLE 27-Ton MSHA Permissible Locomotives Boosting Safe Work Environment at Major Los Angeles Tunneling Project

Brookville Equipment Corporation (BROOKVILLE) recently shipped three 27-ton MSHA-permissible tunneling locomotives to the Walsh-Shea Corridor Constructors for use on the Crenshaw/LAX Transit Corridor Tunnel Project in Los Angeles. By design, the locomotives reduce the risk of explosion due to geological conditions that may host the presence of methane and other combustible gases. Cal-OSHA has classified the tunnel drives on this project "gassy", mandating the use of MSHA permissible locomotives.

The 27-ton locomotives' special safety features include air start, an enclosed engine block, an exhaust filtration system, wiring and piping guards, and an intake flame arrestor, among other upgrades, to fully comply with MSHA's permissibility requirements. Featuring an 8.3L Cummins six-cylinder diesel engine and four-speed transmission, the 185-horsepower locomotives operate on 36-inch rail gauge underground for Walsh-Shea Corridor Constructors .

"BROOKVILLE was selected based on past performance, simplicity of operation and diagnostics, their ability to communicate locally with MSHA, and knowing we would be dealing with the good people of Brookville, PA, U.S.A," said Walsh-Shea Corridor Constructors Tunnel Construction Manager David Girard, P.E.

McMillen Jacobs Associates

McMillen Jacobs Associates is the combination of two rich histories creating one great future. In December 2014, Jacobs Associates, Inc. and McMillen, LLC merged to bring together the combination of over 75 years of technical engineering design and construction expertise in the conveyance (water, wastewater, stormwater), dispute resolution, energy and power, transportation, underground, and water resources industries.

We offer a full range of design, design-build, self-performing construction and construction management services. We work closely with our clients at every stage of a project, assisting them with planning, design expertise, project management, construction, and start-up. Our 21 offices in North America and Australasia and more than 400 staff serve clients locally and worldwide.

McMILLEN JACOBS ASSOCIATES

Design with Vision, Build with Integrity
www.mcmjac.com

HIC Fibers is selling direct in North and South America

HIC Fibers, Inc. has opened offices in Los Angeles, California for North America and Lima, Peru for Central and South America.

This marks the first time that HIC Corp. based in Korea, has opened offices with the intention of selling direct to the end user in lieu of selling strictly through distributors.

HIC Fibers has the exclusive technology and rich know-how in manufacturing of steel fibers. HIC Fibers can provide you a steel fiber of your choice in length, diameter and package.

Contact HIC Fibers direct at (323)-935-4500 or visit us on the web at HIC Fibers.com

HIC Fibers, Inc.
4801 Wilshire Blvd., Ste. 305
Los Angeles, CA 90010 USA
Telephone: +1-323-935-4500
Email: sergi.kim@hicfibers.com
Contact: Sergi Kim
www.HICFibers.com

HIC Fibers

Announcing Doctor Mole Incorporated

Dr. Gary S. Brierley started operating as an independent consultant under the corporate name of Doctor Mole Incorporated (DMI) on January 1, 2013. Doctor Mole Incorporated is a one-stop-shopping-center for the design of all types of underground openings in all types of ground conditions. DMI can help clients meet their underground design and construction needs. No job is too small and it is our intention to help owners, designers, contractors, geotechnical engineers, and developers create successful underground projects from start to finish. Based in Denver, Colorado, DMI is strategically located and available to help with projects across the United States. Give us a call at 303.797.1728 or visit us on the web at www.drmoleinc.com.

Doctor Mole Incorporated
990 S. Broadway, Suite 222
Denver, CO 80209 USA
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- Caverns
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- Pre-bids
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- Dispute Resolution
- Claims
- Forensic Investigations
- Geotechnical Report Preparation

For more information contact:

Gary Brierley

gbrierley@drmoleinc.com or 303.797.1728

The Heintzmann Group

The Heintzmann Group, which has been in business approximately 165 years, manufactures support systems in the tunneling and mining industries. In the last decade, we have greatly expanded our line of products, as well as our regions of service. We currently have offices located in Virginia, West Virginia, Alabama, Colorado, and Illinois. Our range of products and services include but are not limited to standing supports, pumpable roof support, arches, square sets, pre-stressing devices, heat treated beams, polyurethane grout injection, shaft rings, lattice girders, two flange liner plates and four flange liner plates.

The goal of the Heintzmann Group is to provide resources to make the tunneling and mining environments safer and to achieve the highest level of customer satisfaction by providing our customers with a variety of support options.

The Heintzmann Group
Telephone: +1-276-964-7413
www.heintzmann.com

Bradshaw Offers Innovative Tunnel Engineering and Construction Technology

Bradshaw Construction Corporation strives to apply the most appropriate tunneling technology to each project based on its purpose, subsurface conditions and surface restrictions. The company's management team is proud of its ability to construct any type of tunnel in any soil condition both above and below the water table. From small hand mined, wood-box and liner plate tunnels to large NATM shotcrete-lined tunnels; from small pilot tube guided auger bores to large rib-and-board shield and tunnel boring machine (TBM) tunnels; from conventional pipe jacking to slurry microtunneling (MTBM) to earth pressure balance (EPB) TBM tunnels; and from hand mined drill and blast to rock tunnel boring machines (TBMs), Bradshaw Construction has a solution.

For your next project, let our knowledgeable staff of tunnel engineers and construction professionals create the most cost effective, safest, and highest quality solution for your unique tunneling needs.

Bradshaw Construction Corporation
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Fax: +1-410-970-8340
www.bradshawcc.com

David R. Klug & Associates, Inc.

David R. Klug & Associates, Inc. provides international and national manufacturers representative services to the underground heavy civil and mine construction industries. The company specializes in the sale and coordination of specialty products, equipment and services for soft ground, conventional and NATM/SEM tunneling practices. Expertise is offered in the supply of various componentry used in the manufacture of one pass precast segmental tunnel linings inclusive of EPDM gaskets, plastic and steel connectors, grout lifting assemblies and precision steel segment casting moulds plus final lining forming systems for C-I-P final lining applications. Through their distribution company, Klug Construction Systems, LLC offers GFRP rock bolts and soft-eyes, steel and synthetic fiber reinforcement, prefabricated welded wire fabric and rebar reinforcing panels plus specialty grout systems for various tunnel backfill grout requirements for highway, rail, subway, water and CSO tunnel construction applications.

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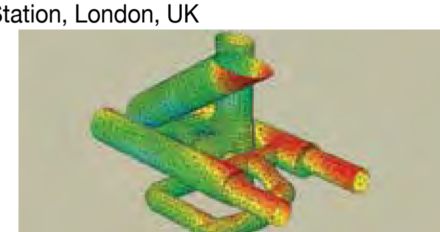
Website: www.drklug.com

Dr. Sauer & Partners

Dr. Sauer & Partners is an independent consultancy specialised in providing the full range of design and construction management services for SEM tunnels, shafts and caverns. The firm delivers innovative, cost-effective and environmentally-aware design solutions and has over 30 years of experience providing design and construction for more than one hundred of the world's most complex tunnelling projects (Metro, Highway, Water, Rail and Mining). Dr. Sauer & Partners designs tunnels in urban and rural locations and in any type of geology. Current and recent projects include: Chinatown Station (San Francisco, USA), Ottawa Light Rail (CAN), Bank Station Capacity Upgrade Project (London, UK), Crossrail (London, UK), Red Line (Tel Aviv, Israel), Eglinton Crosstown LRT (CAN)

The image shows: 3D FE Model of Step Free Access at Green Park Station, London, UK



Custom Tunneling Equipment Design & Production Specialists

Custom Tunneling Equipment Design & Production Specialists
Kelley Engineered Equipment, LLC was founded in 2007 by Brian and Cindy Kelley. The company has a growing staff of mechanical engineers, control system technicians, designers and drafters with extensive equipment design experience. Brian has nearly 30 years of tunneling equipment design experience at Robbins, Kiewit and Kelley Engineered Equipment. Jesse Schneider has been added to the engineering team. Jesse has 10 years of experience in tunneling and tunneling equipment design at Frontier Kemper. Recently, Jay White has joined the team as shop operations manager. Mike Toczek, and Anna Thayer have also recently joined the engineering staff. Mike has a BSME from UNL and Anna will graduate with a BSME from UNL in May. The company specializes in custom equipment design, including lifting systems, mucking systems, gantries, pipe carriers, trailing gear, custom attachments, conveyors, lift cars, equipment modifications, ventilation systems, heavy load handling systems, custom cranes, personnel access systems and more. **See www.KEELLC.com.**

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Surecrete Inc.

Surecrete Inc. specializes in furnishing bagged cementitious materials, mixing and placing equipment, and related accessories to the heavy civil tunnel, geotechnical and mining markets.

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We also represent several major equipment manufacturers focusing on the mixing and placing of shotcrete, concrete and grouts.

Surecrete Inc.

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AWARDS

Martin Herrenknecht receives the von Siemens ring award

Martin Herrenknecht (SME) received the Werner von Siemens Ring, one of the most prestigious technical engineering awards, on Dec. 13, 2016 at the Berlin-Brandenburg Academy of Sciences and Humanities. The engineer and entrepreneur received the award for his outstanding life achievements in the technical development of gigantic tunnel boring machines.

The ring was presented by Prof. Dr. Joachim Ullrich, chairman of Foundation Council l at the Werner von Siemens Ring Foundation and president of the Physikalisch-Technische Bundesanstalt. The Werner von Siemens Ring Foundation highlighted Herrenknecht's involvement in the development of tunnel boring machines and honored his technical pioneer spirit in groundbreaking engineering projects in mechanized tunneling. For the past 100 years, the Werner von Siemens Ring has been awarded to inventors and entrepreneurs for outstanding achievements who, like Werner von Siemens, realized epoch-making technical innovations and guided them to success. ■

Joachim Ullrich (l), presented the Werner von Siemens ring award to tunnel pioneer Martin Herrenknecht (r).

Lee Tunnel project wins concrete award using Dramix 5D steel fibers

The Lee Tunnel in Beckton, London, UK, is a Morgan Sindall/Vinci Grand Projects and Bachy Soletanche joint-venture (MVB JV) project and the first tunnel to win the prestigious Concrete Society Award.

The steel fiber-reinforced concrete tunnel project is comprised of five shafts and, at 90 k (56 miles), the diaphragm walls are the deepest recently undertaken in the UK. A 7 m- (23 ft-) diameter, 7 km- (4.3 mile-) long tunnel connects the shafts. The innovative Dramix 5D steel fiber-reinforced concrete (SFRC) used for the slip-formed tunnel lining took 18 months to develop, resulting in a steel fiber-reinforced self-compacting concrete. The five shafts were also designed and constructed using an innovative slip-formed type of shaft construction that incorporated steel fiber- reinforced concrete. This substantially reduced the quantity of structural reinforcement, enabling a faster and safer construction process.

The Dramix 5D steel fibers provided excellent bending hardening properties to the concrete section, thanks to high ductility wire, ultra-high tensile strength and perfectly shaped hooks. When the designer and MVB JV replaced 17 kt (18,739 st) of rebar with more than 2 kt (2,205 st) of the Dramix 5D steel fibers they eliminated a large and difficult logistical challenge. The Dramix 5D series provides designers with new opportunities to design steel fiber concrete

(Continued on page 68)

Lee Tunnel in Beckton, London, UK.

PERSONAL NEWS

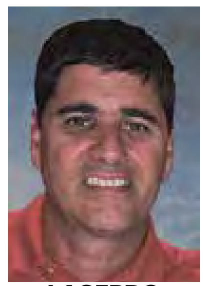
CONRAD W. FELICE (SME) Ph.D., managing principal of C.W. Felice LLC, was elected a Fellow of the American Society of Civil Engineers (ASCE) in December 2016. This recognizes a level of professional distinction and achievement achieved by fewer than 3.5 percent of ASCE members. Felice is a current trustee for Deep Foundations Institute, chair of the Transportation Research Board's Tunnels and Structures Committee, a member of the ASCE committee on underground engineering and construction, and serves as vice chair on the industry advisory committee for the Department of Mining Engineering at the Colorado School of Mines.


FELICE

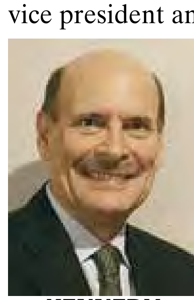
MIKE RISPIN (SME), senior vice president for global sales and marketing at the Normet Group, announced the following changes in Normet's North American organization, effective Dec. 1, 2016. **GREGORY HALLETT** (SME) joins the Normet Group as vice president, North America and managing director, Normet Americas. Hallett is an experienced manager with 30 years in the construction and mining industries. He will work from the North America headquarters in Salt Lake City, UT. **LAURO LACERDA** (SME) joins the organization as manager of Ground Control and Construction Technologies, heading up the construction chemical and rock reinforcement business in North America. He has more than 32 years of experience in the mining and tunneling industry sectors and is a licensed professional engineer in Nevada. He will report to Hallett. **ROB STEPAN** has joined Normet as product revelopment and production coordinator for Construction Chemicals, supporting the company's growing tunnel boring machine effort as well as the other facets of the construction chemicals business in North America. He will work from Cleveland, OH and report to Lacerda.


RISPIN


HALLETT

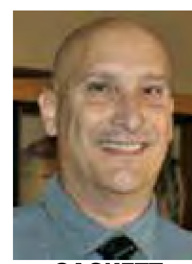

LACERDO

EDWARD R. KENNEDY (SME) has joined Shannon & Wilson as a vice president and senior project manager for Tunnels and Systems. He has more than 40 years of experience in all major phases of heavy civil construction projects and significant expertise with soft ground and hard rock tunnel boring machines (TBM). Kennedy has served as resident engineer for large, complex water/wastewater, transportation and other infrastructure-related projects in challenging urban environments. He is also an established leader and innovator in the tunneling and underground industry having participated in much of the development history of the TBM, working with Robbins. He also has worked on the design, operation and troubleshooting of soft ground and hard rock TBMs around the world.


KENNEDY

Shannon & Wilson has also announced the following promotions for 2017: **CHRISTOPHER DARRAH** to vice president, **JERI-BETH BOWMAN** to senior associate, and **JEREMY BUTKOVICH, ANDY CANEDAY, KATHY CORBETT, MATT GIBSON, KATHRYN PETEK** and **TYLER STEPHENS** to associate.

Brierley Associates has opened a new Norfolk, VA office under the management of **DAVID SACKETT,** PG. Sackett has more than 30 years of domestic and international experience as a geoscientist, and he is a licensed professional geologist in Virginia and Texas. He has been responsible for the acquisition and management of geological interpretations of high-resolution marine geophysical data, nearshore and landside site characterization, planning and execution


SACKETT

(Continued on page 69)

Lee Tunnel

(Continued from page 67)

structures for underground and surface works and enables contractors to build faster and safer solutions.

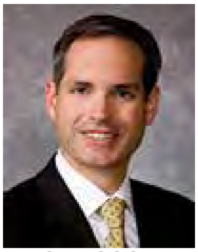
According to the judging panel, the Lee Tunnel, which will help prevent 16 mt (17.6 million st) of sewage entering the River Lee and Thames each year, was the most outstanding structure and therefore outright winner for its technical achievements in the use of concrete, its demanding placement conditions and innovative structural solutions. The statistics for concrete volume placed are impressive, and the innovation required and final execution is exemplary. This project pushed the technical boundaries of what is possible with concrete. ■

PERSONAL NEWS

(Continued from page 68)

of integrated geotechnical investigations, preparation of geological and geotechnical reports and technical reviews in English and Spanish.

Brierley has also opened new offices in Milwaukee, WI and Chicago, IL under the direction of **JON (IKE) ISAACSON,** PG, PE, who has more than 16 years of domestic and international experience as an



ISAACSON

engineering geologist and tunnel engineer. He has been responsible for the planning and execution of numerous land and offshore geotechnical investigations, field reconnaissance/mapping programs in remote areas, and site characterizations for tunnels and dams. He also has experience in physical and remote inspection of transportation and water tunnels, tunnel rehabilitation, ground freezing, grouting, tunnel construction, hyperbaric interventions, resident engineering, constructability, monitoring data interpretation, ground loss mapping and remediation. ■

NEW PRODUCTS

Robbins small boring unit finishes crossing two weeks early

The Robbins remote controlled small boring unit (SBU-RC) is a new type of boring machine capable of excavating small-diameter, hard rock tunnels at long distances, on line and grade. The SBU-RC is currently manufactured in the 900-mm (36-in.) diameter range, but it could be designed as small as 750 mm (30 in.) in diameter. It features a smart guidance system for pinpoint steering accuracy and is controlled from an operator's station on the surface. Muck removal is accomplished through a vacuum system, making the Robbins SBU-RC more cost effective than microtunnel boring machines requiring slurry and cleaning plants onsite.

A Robbins 900-mm (36-in.) SBU-RC completed a critical hard rock crossing below railroad tracks two weeks early in Bend, OR, breaking through on May 5, 2015. The SBU-RC holed through on line and grade after achieving up to 15 m (50 ft) of advance per day in abrasive basalt rock up to 48 MPa (7,000 psi) ultraconfined compressive strength.

The machine operates much like a motorized small boring unit with a circular cutterhead and cutting tools that can excavate hard rock or mixed ground conditions. An in-shield drive motor provides torque to the cutterhead, while a pipe jacking system or auger boring machine provides thrust. There is no manned entry. It eliminates the human element, so it is safer, and there is no need for ventilation when there is a worker in the tunnel. There is no slurry to mix or contend with, and there is a clean and dry pit, with no spoils to remove.

The cost-effective SBU-RC is also available for lease. ■

The Robbins SBU-RC is equipped with a smart guidance system by TACS to show projections of the future bore path.

T&UC TUNNEL DEMAND

COMPILED BY JONATHAN KLUG, DAVID R. KLUG & ASSOCIATES

TUNNEL NAME	OWNER	LOCATION	STATE	TUNNEL USE	LENGTH (FEET)	WIDTH (FEET)	BID YEAR	STATUS
Gateway Tunnel	Amtrak	Newark	NJ	Subway	14,600	24.5	2018	Under study
2nd Ave. Phase 2	NYC-MTA	New York	NY	Subway	16,000	20	2020	Under design
2nd Ave. Phase 2-4	NYC-MTA	New York	NY	Subway	105,600	20	2017-22	Under study
Water Tunnel #3 Stage 3 Kensico	NYC-DEP	New York	NY	Water	84,000	20	2020	Under design
Bergen Point Wastewater Outfall	Suffolk Co., DPW	Babalon	NY	Sewer	14,200	12	2017	Under design
Cross Harbor Freight Tunnel	NYC Reg. Develop. Authority	New York	NY	Rail	25,000	30	2022	Under study
Amtrak B&P Tunnel	Amtrak	Baltimore	MD	Rail	10,000	30	2018	Under design
Thimble Shoal Parallel Tunnel	Chesapeake Bay Bridge & Tunnel Dist.	Chesapeake	VA	Highway	5,700	45	2016	Dragados/ Schiavone awarded
Northeast Boundary Tunnel	DC Water and Sewer Authority	Washington	DC	CSO	17,500	23	2017	Bid Date 03/01/2017
Potomac River CSO Tunnel	DC Water and Sewer Authority	Washington	DC	CSO	4,500	33	2022	Under design
Olentangy Relief Sewer Tunnel	City of Columbus	Columbus	OH	Sewer	58,000	14	2017	Under design
Alum Creek Relief Tunnel Phase 1 Phase 2	City of Columbus	Columbus	OH	Sewer	30,000 21,000	18 14	2018 2019	Bid date 03/07/17
Doan Valley Storage Tunnel	NEORSD	Cleveland	OH	CSO	9,700	17	2017	Under design
Westerly Main Storage Tunnel	NEORSD	Cleveland	OH	CSO	12,300	24	2020	Under design
Shoreline Storage Tunnel	NEORSD	Cleveland	OH	CSO	16,100	21	2021	Under design
Shoreline Consolidation Tunnel	NEORSD	Cleveland	OH	CSO	11,700	9.5	2022	Under design
Southerly Storage Tunnel	NEORSD	Cleveland	OH	CSO	17,600	23	2024	Under design
Ohio Canal Interceptor Tunnel	City of Akron	Akron	OH	CSO	6,170	27	2015	Bid date 4th Q 2015
Continental Rail Gateway	CRG Consortium	Detroit	MI	Rail	10,000	28	2015	Under design
ALCOSAN CSO Ohio River Allegheny River Mononghahela River	Allegheny Co. Sanitary Authority	Pittsburgh	PA	CSO	10,000 41,700 53,900	30 30 30	2019 2020 2021	Under design Under design Under design
Three Rivers Protection/Overflow	City of Fort Wayne	Fort Wayne	IN	CSO	26,400	12	2016	Bid date 2/16/2017
Louisville MSD Tunnel	Lousville MSD	Lousville	KY	CSO	13,200	22	2018	Under design
Deer Creek Sanitary Tunnel	St. Louis MSD	St. Louis	MO	CSO	21,000	19	2016	JayDee/Frontier Kemper low bid
Lower & Middle River Des Peres Storage Tunnel	St. Louis MSD	St. Louis	MO	CSO	47,500	30	2020	Under design

TUNNEL NAME	OWNER	LOCATION	STATE	TUNNEL USE	LENGTH (FEET)	WIDTH (FEET)	BID YEAR	STATUS
Lower Meramec Tunnel	St. Louis MSD	St. Louis	MO	CSO	35,900	8	2020	Under design
KCMO Overflow Control program	City of Kansas City, MO	Kansas City	MO	CSO	62,200	14	2018	Under design
Mill Creek Peaks Branch Tunnel	City of Dallas	Dallas	TX	CSO	5,500	26	2014	To be rebid
Ballard to Wallingford Tunnel	Seattle Public Utilities	Seattle	WA	CSO	14,250	14	2018	Under design
L.A. Metro Westside Phase 2 Phase 3	Los Angeles MTA	Los Angeles	CA	Subway	 26,500 26,500	 20 20	 2016 2017	Tutor Perini/O&G JV low bidder Under design
Speulvada Pass Corridor	Los Angeles MTA	Los Angeles	CA	High/Trans.	55,500	60	2018	Under study
Northeast Interceptor Sewer 2A	LA Dept. of Water and Power	Los Angeles	CA	Sewer	18,500	18	2014	Delayed indefinately
River Supply Conduit - Unit 7	LA Dept. of Water and Power	Los Angeles	CA	Water	13,500	12	2015	Advertize 03/2017
JWPCP Effluent Outfall Tunnel project	Sanitation Districts of LA	Los Angeles	CA	Sewer	37,000	18	2015	Advertize 02/2017
Two Mile Bar Tunnel	Oakdale Irrigation	Oakdale	CA	Water	5,950	11.5x13	2017	SMCI low bidder
Freeway 710 Tunnel	CALTRANS	Long Beach	CA	Highway	26,400	38	2016	Under design
BDCP Tunnel #1 BDCP Tunnel # 2	Bay Delta Conservation Plan	Sacramento	CA	Water	26,000 369,600	29 35	2018 2019	Under design Under design
SVRT BART	Santa Clara Valley Trans Authority	San Jose	CA	Subway	22,700	20	2016	Redesign activated
Silicon Valley Clean Water Tunnel	Silicon Valley Clean Water	Silicon Valley	CA	CSO	17,500	13	2017	Under design
Coxwell Bypass Tunnel program	City of Toronto	Toronto	ON	CSO	35,000	12	2015	Advertize 3Q 2017
Keswick Effluent Outfall	City of Toronto	Toronto	ON	CSO	11,600	23	2018	Under design
Yonge St. Extension	Toronto Transit Commission	Toronto	ON	Subway	15,000	18	2016	Under study
Taylor Massey Tunnel	City of Toronto	Toronto	ON	CSO	20,000	18	2018	Under design
Inner Harbour West	City of Toronto	Toronto	ON	CSO	18,400	19	2021	Under design
Scarborough Rapid Transit Extension	Toronto Transit Commission	Toronto	ON	Subway	25,000	18	2017	Under design/ delayed
REM Transit Tunnel	City of Montreal	Montreal	QC	Subway	27,000	22	2017	Bidders selected
Newfoundland-Labrador Fixed Link	Gov. of Newfoundland/Lab	Newfoundland	NL	Transit	56,000	40	2020	Under study
Green Line LRT	City of Calgary	Calgary	AB	Traansit	26,250	20	2018	Under design
Second Narrows Tunnel	City of Vancouver	Vancouver	BC	CSO	3,600	14	2013	Under design
Annacis Island Outfall	City of Vancouver	Vancouver	BC	Water	8,000	10	2017	Under design
Burnaby Mountain	Kinder Morgan	Vancouver	BC	Oil	8,000	12	2017	Under design
UBC Line project	Trans Link	Vancouver	BC	Subway	12,000	18	2015	Under design
Northern Gateway Hoult Tunnel	Enbridge Northern	Kitimat	BC	Oil	23,000	20	2014	Under design

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