t&uc®
Tunneling & Underground Construction
The Official Publication of UCA of SME
www.TUCmagazine.com
Volume 14 NO. 2 May 2020

Arkansas Tunnel studies
Autonomous tunnel boring
TBMs for hydropower projects

Special Editorial Supplement from the publisher of Mining engineering

May Contents

Cover Story

In This Issue

On page 20, the Arkansas State Highway and Transportation Department initiated a high-level tunnel feasibility study for a proposed east-west arterial highway under Hot Springs National Park to bypass and lessen traffic conditions in the historic city of Hot Springs. On page 34, Mike Mooney and his co-authors look to lessons learned from the autonomous-vehicle framework.

Feature Articles

tucmagazine.com

AN OFFICIAL PUBLICATION OF UCA OF SME | WWW.SMENET.ORG | VOLUME 14 NO. 2 | MAY 2020

Special editorial section from the publisher of Mining Engineering

Take advantage of your membership in these unique times

The past few months have been extraordinary and there looks to be no reasonable way to get back to normal in the upcoming weeks and even months ahead. This even assumes that what was considered normal before the COVID-19 shutdown will become normal again.

With no travel plans and everybody now working from home, what better time to investigate ways to support your industry and the UCA?

COVID-19 has wreaked havoc on meetings and events this spring, from the NBA and NHL playoffs, to Major League Baseball's Opening Day and the postponement of tunneling industry events such as the World Tunneling Congress and NoDig. You should have already received a notification that the UCA of SME is not exempt from this phenomenon with the cancellation of the North American Tunneling (NAT) conference in Nashville, TN that was scheduled for June 7-10.

As you can imagine, the logistics of making such a decision are complicated and yet, given the situation with COVID-19 at the moment, it was not a difficult decision to make. The health and welfare of the industry and all attendees is everybody's highest priority. Given that we will miss out on NAT, our focus now turns to the Cutting Edge Conference (Dallas, TX, Nov. 9-11) as the largest event on the UCA of SME calendar.

Cutting Edge will take place in Dallas, TX and will be the usual blend of technical presentations, discussion panels, extended question-and-answer sessions with the authors and plenty of networking opportunities in an exhibit hall with small tabletop-style booths. For those who have not attended previously, perhaps the wreckage of this year brings an opportunity for us all to meet in Dallas and experience a slightly different, but equally high-quality UCA of SME meeting.

As this pandemic changes the way we work and interact, I've spoken to people working on their decks at home in the sunshine and others working in their basements. Wherever you are reading this, I suggest that you take a moment this spring and peruse the excellent SME bookstore. Why not purchase and read a copy of the *History of Tunneling in the United States*, or obtain one of the other excellent guideline documents for your technical library.

While you are browsing the bookstore, I ask you to look with a somewhat critical eye as well. If there is something you expected or wanted to see but did not, consider making me or any member of the executive committee aware of this missing item in our umbrella of technical guideline documents.

You could volunteer to take on a leadership role and produce this guideline yourself or simply make us aware of the need, and we can pick it up from there and find somebody to lead the charge.

We are always seeking better ways to be more connected to the industry and be responsive to your needs. You are the industry and should drive the bus when it comes to ideas that you want the UCA to pursue. My job is to respond and direct traffic to make sure your needs are fulfilled by UCA of SME, which is YOUR industry organization. I'll continue to do this — wherever we happen to be working. Keep well and safe and I look forward to seeing you all in Dallas at Cutting Edge, if not before. ■

Robert JF Goodfellow,
UCA of SME Chair

EDITORIAL STAFF

Editor
Willaim Gleason
gleason@smenet.org

Senior Editor
Georgene Renner
renner@smenet.org

Associate Editor
Margo Ellis
ellis@smenet.org

Production Graphic Artist
Ted Robertson
robertson@smenet.org

BUSINESS STAFF

Media Manager
Advertising
Gary Garvey
garvey@smenet.org

Phone +1-800-763-3132 or +1-303-973-4200
Fax +1-303-973-3845

Internet www.smenet.org

Highway connection through Ouachita Mountains — Arkansas Tunnel study

The Arkansas State Highway and Transportation Department (AHTD) initiated a high-level tunnel feasibility study for the proposed East-West arterial highway under Hot Springs National Park as part of its due-diligence comparison of an open-cut versus a tunnel option to create a bypass to lessen traffic impacts on historic Hot Springs. The new tunnel on the proposed East-West bypass highway would be situated approximately 2 km (1.25 miles) north of a planned intersection with Highway 70, as shown in Fig. 1. The tunnel study addressed feasibility, constructability and conceptual cost and schedule estimates for a new tunnel alignment through elevated ridge terrain featuring an extremely hard novaculite formation. Considering the existing site topography and local geologic conditions, an appropriate tunnel construction strategy, including temporary and permanent tunnel support, was developed. Considering the highly fractured nature of the novaculite, a sequential excavation method (SEM) tunneling approach was developed. The SEM approach was cost estimated and scheduled for comparison with the open-cut alternative.

FIG.1

Location plan of proposed highway tunnel.

Eric Wang, Ray Sandiford and Michael Fugett

Eric Wang and Ray Sandiford, members UCA of SME, are principal engineer & associate vice president and vice president and east practice lead, respectively, HNTB National Tunnel Practice. and Michael Fugett is assistant chief engineer, Arkansas State Highway & Transportation Department, email ewang@hntb.com.

Existing conditions

Geologic setting. The tunnel alignment passes through a prominent ridge of the Ouachita Mountains, which consist of outcrops of the Big Fort Chert, the Arkansas Novaculite and the Stanley Shale. Novaculite is the predominant geologic formation of the ridge, as the less resistant rock has been eroded over time. Novaculite is a dense, hard, fine-grained, siliceous metamorphic rock. It is a subcategory of chert, which has transformed into novaculite after low-grade metamorphism.

Physical properties. Novaculite is a very hard and very dense rock that varies in color from white to gray-black. Novaculite is not only difficult to core with very slow drilling rates but also yields minimal rock recovery due to very brittle properties. Table 1 presents generalized engineering properties of novaculite, which are subject to confirmation based on a site-specific investigation

TABLE 1

Generalized engineering properties of novaculite.

Grain size	Hardness	Fracture	Porosity	Compressive strength (psi)	Toughness	Specific gravity	Density (pcf)
Micro-crystalline	7	Conchoidal	Very low	65,270	1.5	2.5 - 2.7	162 - 169

and laboratory testing program including rock mass characterization data.

The difficulties encountered during coring attempts should not be considered as anticipated behavior for the drilling of holes for blasting and/or rock bolting. In fact, percussion drilling can be successfully performed in brittle rock, as brittle rocks do break or spall under concentrated loading. However, increased bit wear should be anticipated due to the relative hardness of the rock. Novaculite's microcrystalline structure makes it both very hard and very brittle. The formation has also been subjected to tectonically induced folding, which has caused extensive fracture patterns in the rock as shown in Fig. 2.

FIG.2

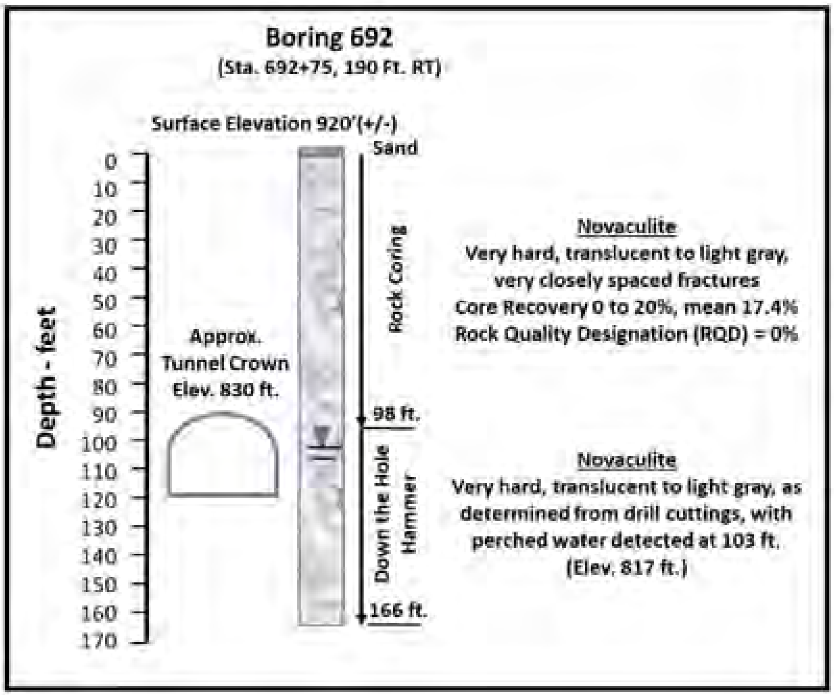
Folding in novaculite formation.

Subsurface profile and ground water conditions. Difficult drilling access due to remote site location and mountainous terrain limited the available subsurface data to a single test boring shown in Fig. 3 with the approximate tunnel horizon.

Ground water was encountered in boring 692 at an approximate elevation of 250 m (817 ft). This indicates a ground-water level approximately 3 m (10 ft) above the tunnel invert. The temperature of the ground water encountered during mining is anticipated to be comparable to the ambient air temperature of the area. The ground water may contain a higher-than-normal concentration of silica due to migration through silica-rich novaculite. Fortunately, silica is not detrimental to either typical waterproofing materials or in-place concrete. The current tunnel design concept considers a watertight (partially tanked) system (Fig. 4) allowing ground water to flow around the tunnel structure and either bypass the tunnel or drain into a subdrain system. The impact of potential localized depression of the ground-water table would be evaluated during subsequent phases of design. A hydrogeologic analysis would also assist in developing drainage design as well as consideration of an alternative, fully enclosed waterproofing concept.

FIG.3

General subsurface profile for proposed tunnel.

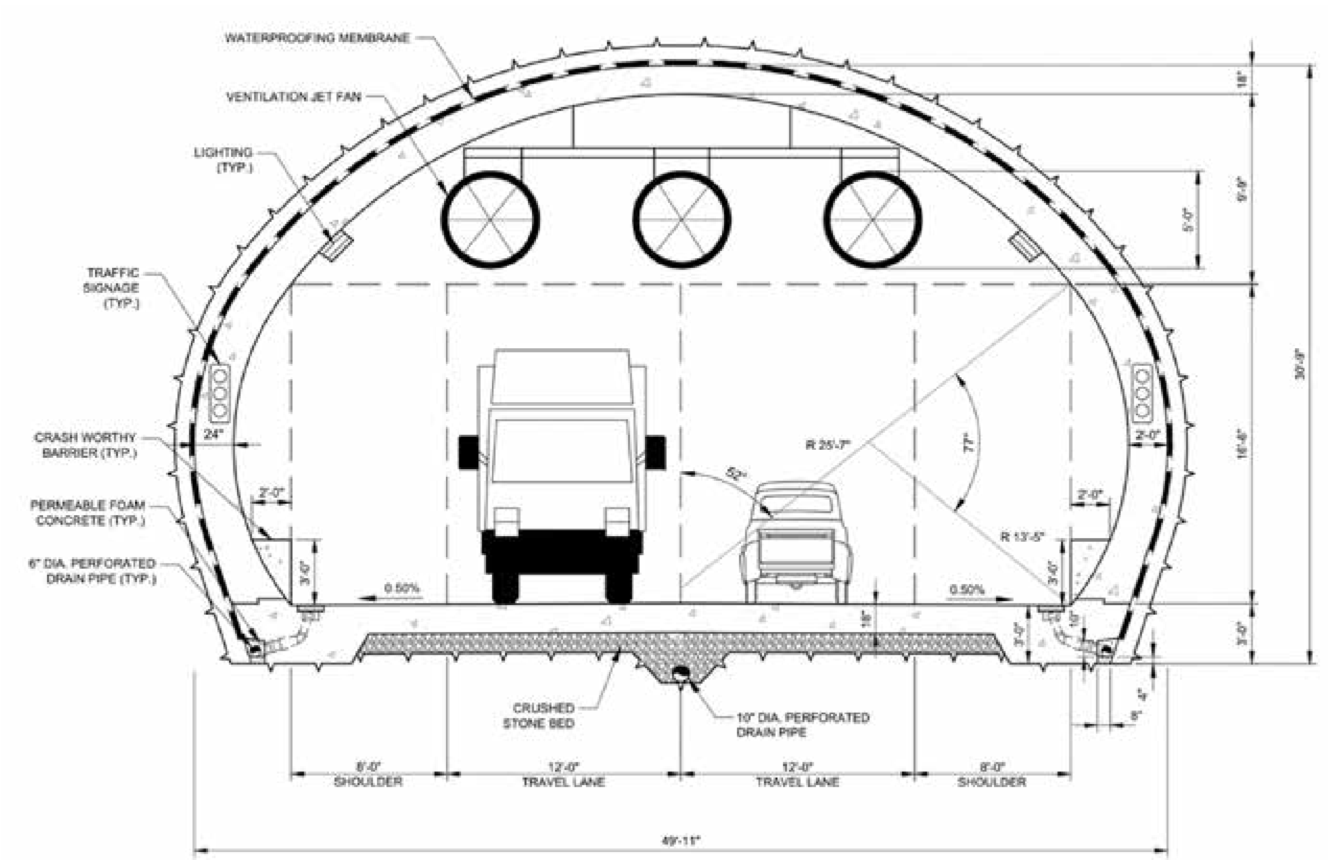


Tunnel design basis

General configuration. Considering a 5.5 percent roadway grade, the proposed

FIG.4

Tunnel space proofing.



two-lane vehicular highway tunnel extension will be approximately 365 m (1,200 ft) long. The tunnel study is based on a straight horizontal alignment crossing through the Hot Springs National Park Mountain in Arkansas accommodating a vertical curve with a high point midway between the portals. The relatively short length of tunnel and the existing rock formation favor mining by sequential excavation method. The cross section provided in Fig. 4 had been developed in conformance with the most suitable shapes for this type of tunnel and the specific space requirements of a two-lane highway tunnel.

Rock loading. The study considered a permanent reinforced concrete tunnel lining to be constructed

TABLE 2

Rock loads using Terzaghi system.

Rock Condition: Very blocky, seamy and shattered			
Tunnel Width B 52 ft Tunnel Height H 32.5 ft C = B + H 84.5 ft Unit Weight γ 169 pcf Moisture γ 174 pcf			
Load type	Estimated rock height	Estimated rock loads	Equivalent rock height, h (ft)
Initial Avg 0.3C	25 ft	2.2 ksf	13
Initial Upper 0.6C	51 ft	4.4 ksf	25
Final Lower 0.35B	18 ft	1.6 ksf	9
Final Avg (0.35B+1.1C)/2	56 ft	4.8 ksf	28
Final Upper 1.1C	93 ft	8.1 ksf	46

FIG.5

Rock loads using rock mass quality (Q) system.

The rock mass quality, Q-value was assumed to 1 to 5 representing "Poor to Fair" condition and average value of 2.5.

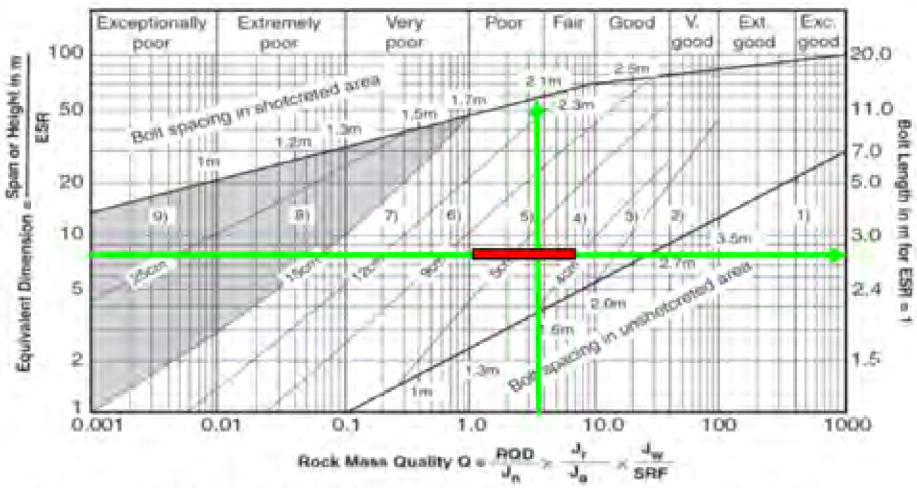


Chart for the design of SFRS support (Grimstad & Barton, 1993)

REINFORCEMENT CATEGORIES

1) Unsupported
2) Spot bolting, sb
3) Systematic bolting, B
4) Systematic bolting (and unreinforced 4 to10cm, B(+S)shotcrete,
5) Fiber reinforced shotcrete and bolting, 5 to 9cm, S(fr)+B
6) Fiber reinforced shotcrete and bolting, 9 to 12cm, S(fr)+B
7) Fiber reinforced shotcrete and bolting, 12 to 15cm, S(fr)+B
8) Fiber reinforced shotcrete > 15cm, reinforced ribs of shotcrete and bolting, S(fr), RRS+B
9) Cast concrete lining,CCA

Max. Dimension at Sequencial Exc.	width	26	ft	8	meter
	height	18	ft	6	meter

	Lower Bound	Avg.	Upper Bound
Dowel length, ft	9	9	9
Dowel spacing, ft	6	7	8
Thickness shotcrete, in	3	2	2

B = 52 ft

Jr = 1.5 (Joint Roughness)

	Upper Bound	Avg.	Lower Bound
Q	1	2.5	5
Support Pressure, Pv (ksf)	8.8	6.5	5.2
Equivelent rock height, (ft)	51	37	30


SmartPower™
OUR
KIND OF
PLAYGROUND
This is the natural habitat for Brokk's compact giants. With the perfect combination of power, operability and accessibility our demolition robots provide eff icient solutions to increase profits.
Intelligent Demolition Power
BROKK®
Brokk Inc. | Monroe, WA | 1-360-794-1277 | info@brokkinc.com | www.brokk.com

TABLE 3

Material properties used in FEM analysis.

Material type	Ground (Mohr — Coulomb model)	Concrete liner (Elastic model)
Saturated unit weight, g (pcf)	174	150
Factored unit weight, g (pcf)	244	210
Young's modulus, E (ksf)	35,000	580,000
Poisson's ratio, n	0.3	0.3
Cohesion, c (psf)	4,000	N/A
Friction angle, f (deg)	55	N/A

after initial support installed over the entire tunnel length. The tunnel final lining is subject to rock loads imposed by the overburden, the surrounding ground and hydrostatic pressure from ground water. The lining will be subject to minimal hydrostatic pressure due to the location of the ground water, which is only 3 m (10 ft) above the tunnel invert. The hydrostatic pressure is anticipated to decrease over time due to the tunnel's pressure relief and drainage system.

A top heading and bench sequential excavation scheme assuming 1.2-m (4-ft) round lengths was used in the tunnel study. An initial rock support system consisting of spiles, lattice girders, shotcrete and rock dowels was considered installed immediately after the full cross section was excavated over the length of the round. Upon completion of the excavation and installation of initial support, drainage and waterproofing, the final liner will be constructed. Rock loads on the completed tunnel primarily impart compressive stresses in the final liner. However, shear and bending stresses will be exerted on various locations in the liner due to the nonuniform curvature of the tunnel cross section and uneven distribution of rock loads. The final liner design thickness and reinforcement will be governed by the combination of these parameters of compressive, shear and moments. Rock-loading estimates were performed using applicable methods, including empirical (Terzaghi, 1946), Norwegian Geological Institute's (NGI) Q-system and, for comparison, a numerical finite-element method (FEM) analysis. Specifically, based on the lone nearby boring log, the rock core within the tunnel excavation zone of influence was reported as hard, slightly weathered novaculite with a variable degree of fracturing and included localized, more closely fractured and ferrous stained zones. Site-visit observation notes and photographs confirmed the presence of moderately to highly fractured rock conditions as well as steep cuts with minimal erosion. Hence, the rock-mass condition was characterized as moderately blocky and seamy (MBS) to very blocky and seamy (VBS) under the Terzaghi rock classification system (Terzaghi, 1946) and as corresponding rock mass quality Q = 1 to 5, representing poor to fair conditions, by NGI's Q-system. Table 2 and Fig. 5 summarize the vertical rock support load and equivalent height of rock using these systems.

The FEM analysis (Table 3 and Fig. 6) was based on a ground-relaxation scheme, conservatively assuming a 30 percent ground relaxation value, in order to evaluate previously determined values as well as internal member forces for final lining design.

Drained versus undrained. Reduction of external forces acting on the final liner is promoted by enveloping the waterproof liner with a geotextile material that will facilitate the draining of ground water, thereby reducing hydrostatic pressure. Water collected at the base of the liner will flow through perforated pipes installed on each side of the tunnel to discharge at portals. The drained condition was considered representative of the tunnel conditions featuring variable ground-water levels reflecting the local topography, indicating limited (< 1.2-m or 10-ft) hydrostatic head.

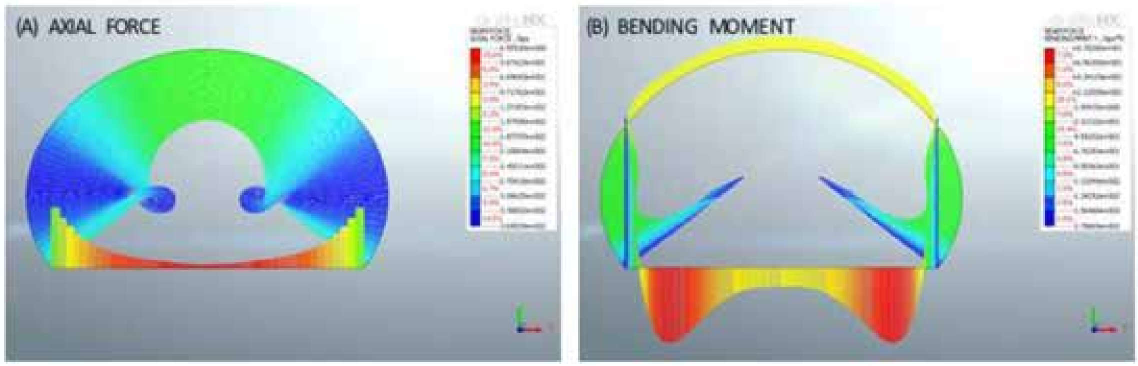
Fire load. Fire effects on the final liner include: (a) additional bending forces due to temperature gradient occurring between the hot interior face and the cool exterior face of the liner, (b) local cracking and explosive spalling of concrete along the face directly exposed to fire and (c) reduction of tensile strength of reinforcing steel. The fire load resulting from combustion of a vehicle is generally assumed to be equivalent to the energy of 50 MW over a two-hour period. Mitigation measures include: (a) incorporating additional bending stresses due to temperature gradient into the design analysis as an extreme loading case to verify integrity of the liner, (b) using polypropylene fibers in the concrete mix to minimize explosive spalling, which help to create voids in the concrete to allow expansion of water vapor and limit buildup of internal pressure, and (c) increasing concrete cover or installing a passive fire protection system to protect reinforcement from being excessively heated (i.e., reduce the thermal exposure of the steel).

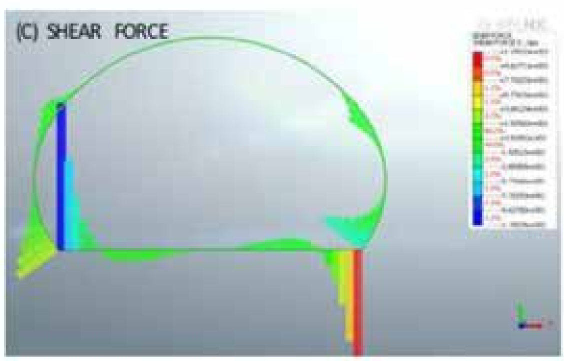
Construction considerations

The tunnel study included the following construction considerations, which informed the development of the cost estimate.

FIG.6

FEM analysis results.





	Max Force (kips/ft)	Corresponded Axial Force (kips/ft)	Corresponded Bending (k-ft/ft)
Axial Force	369		41
Bending Moment	179	249	-
Shear Force	116	146	179

Excavation and support sequence. The predominant rock formation is very hard. However, mechanized excavation methods, including roadheader and backhoe excavator, appear feasible due to the moderately to highly fractured condition of the rock mass. Drill-and-blast excavation does not appear to be necessary based on existing rock mass conditions. Figure 7 shows a feasible excavation sequence totaling five drifts under the top heading and bench arrangement. The proposed initial support system for this type of rock condition includes spiling presupport measures and steel-fiber-reinforced shotcrete (SRFS) with lattice girder and rock dowels on 1.2 m (4 ft)-round length.

Rock drillability. As described in the physical-properties section, the host rock possesses a Moh's relative hardness scale value of 7, corresponding to the upper end of the hardness scale, and hence would require specialty percussion button bits for drilling holes for presupport spiling and rock-support dowels.

Portals. Portal development commences with pre-cut construction via top-down excavation of headwall for the launch portal. The portal construction begins using mechanized rock excavation equipment to build a headwall battered at the steepest stable slope possible based on actual rock-mass orientation, which extends to the proposed portal invert elevation. Anticipated support includes pattern rock dowels combined with structural shotcrete layer. Per Federal Highway Administration (FHWA) recommendations, a portal canopy structure projecting approximately 15 m (50 ft) from the headwall will be constructed as fall protection. Additional fall protection over the portal features a catch-fence device at the base of the slope, which would be subject to periodic maintenance and cleaning. Specifically, the portal canopy section will be constructed of expanded metal liner covered by a nominal 10 cm (4 in.)-thick shotcrete layer externally applied.

Lattice girder encased in nominal 20-cm (8-in.) shotcrete will line the interior side of the metal liner. Waterproofing layer will be installed between the inner shotcrete face and the final cast-in-place concrete lining. Collection of tunnel drainage will be provided by sedimentation (holding) tanks at each portal.

Construction cost estimate

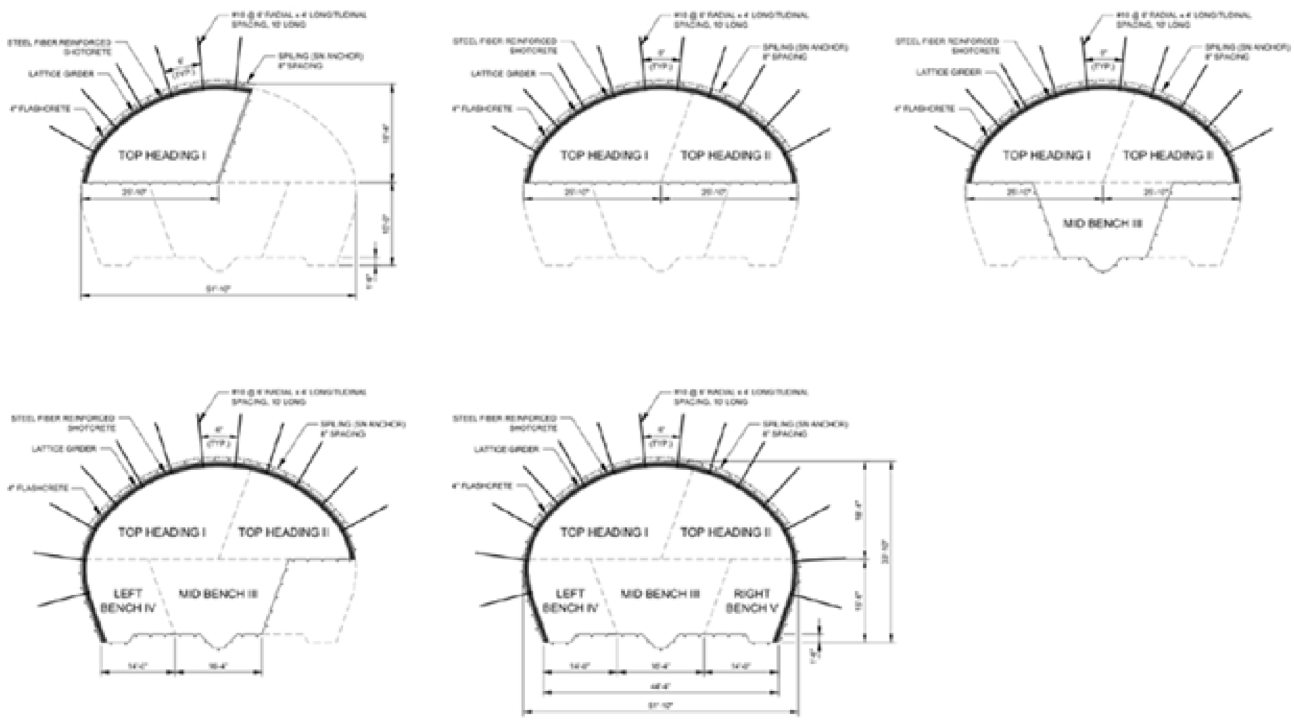
A rough-order-of-magnitude (ROM) construction cost estimate for the 365 m (1,200 ft)-long roadway tunnel based on anticipated material quantities, equipment and crew sizes came to $68 million, including an approximate 10 percent contingency over a 16-month construction duration.

Conclusions

Lessons learned. The results of the tunnel feasibility study indicate that: (a) the tunnel option is constructible

FIG.7

Feasible excavation sequence.



through the prevailing geological formation using mining methods that require commonly available equipment and local workforce, (b) the tunnel option presents an environmentally favorable solution, with minimal surface impacts and (c) an economically sound tunnel solution providing safe highway connection through mountainous terrain is possible. (References available from the authors.) ■

EPB shield tunnel-boring machine automation using the autonomous-vehicle framework

Advances made in self-driving vehicles and automated drilling during the past decade suggest that tunnel-boring machine (TBM) tunneling is headed toward autonomous operation. Automated drilling, primarily adopted in blast-hole drilling for mining, involves driverless surface drill rigs that self-navigate to a predetermined X-Y location and drill at a preset angle (typically vertical) to a target depth. Remote operators oversee the drill rigs and perform some of the operations (de Wardt et al., 2012; de Wardt et al., 2016; Rogers et al., 2019). In current practice, autonomy is limited to auto-positioning of drill rigs, drill-rod handling and drilling fault detection. The main motivation behind automated drilling has been worker safety and workforce shortage in remote area operations. Improvements in production and drilling accuracy have been reported (Kinik et al., 2014; Jacobs, 2015; Lopes et al., 2018). To the authors' knowledge, the drilling process itself has not become intelligent in terms of learning how to drill more efficiently.

Self-driving or autonomous vehicles (AVs) provide a compelling roadmap for autonomous TBM tunneling given the complexity of the technology development, the partial or subsystem adoption demonstrated, the human factor and the likelihood that full autonomy will be realized within the next decade. There are six levels of autonomous driving, levels 0-5 are summarized in Fig. 1. At the time of this writing, AVs on the road perform at level three via a variety of autonomous functions including adaptive cruise control, anticollision self-braking, traffic-jam assist, self-parking and lane-centering assist. Fully AVs, where a driver is not required, and defined by levels four and five, are commercially used in less complex environments (e.g., local shuttle services). However, fully AVs are predicted to occur within the next decade, and no fewer than 1,400 fully AV vehicles are currently in testing by more than 80 companies across 36 states in the United States (Etherington, 2019).

The main motivation behind AV technology is safety. There are approximately 6.5 million motor-vehicle crashes and 37,000 traffic deaths in the United States annually (Insurance Information Institute, 2019). The underlying premise is that AV technology is better at driving than humans are. Data show that collision avoidance technology on current vehicles has improved safety, and predictions are that fully AVs will dramatically improve safety. Another motivation is improved efficiency. With road congestion growing and limited funding to build new transportation capacity, transportation agencies are counting on significant improvements in traffic flow resulting from AVs (Kockelman et al., 2017).

TBM tunneling has advanced considerably over the past two decades, driven by the key performance indicators realized (e.g., production, ground deformation control) and by technology (e.g., sensing, information, electro-mechanization). Automation employed by today's TBMs includes basic subsystem functions including cutterhead rotation speed control (akin to vehicle cruise control), foam injection ratio control and numerous hydraulic and mechanical subsystems. Recently developed and emerging autonomous functions include robotic tool changes (Camus and Moubarak, 2015), ring erection (Martin, 1990; Wu et al., 2011), annulus grouting (Shirlaw et al., 2004) and steering (Shimz Corp., 2018; Schwob et al., 2019). Further, remote operation of TBMs is routinely used in Japan through surface control centers.

Like AVs, the motivation for autonomous shield tunneling is multifaceted and includes safety (of workers and of overlying structures and their inhabitants) and optimization for improved performance (e.g., less downtime, higher production). Cost efficiency is a considerable barrier to growth in underground construction. A key question is what role automation can play in reducing cost.

This article examines autonomous earth pressure balance (EPB) shield tunneling using the development of AVs as a motivating technology. The basic technology of AVs is presented using a sensing–planning–action framework, with noted parallels to TBM tunneling. The development of autonomous EPB shield tunneling subsystems is presented within the sensing–planning–action framework. Subsystems addressed include ground-conditioning optimization, deformation control, chamber pressure control, drive-performance optimization, annulus grouting, steering and ring assembly. The potential benefits of EPB shield automation are discussed, as are the challenges, both technical and nontechnical, including liability and risk.

Autonomous-vehicle framework

A sensing (perception)–planning–action (control) framework is adopted to describe AVs and to translate to autonomous EPB shield tunneling.

Mike Mooney, Hongjie Yu and Rajat Gangrade

Mike Mooney, Hongjie Yu and Rajat Gangrade, members UCA of SME, are Grewcock Chair Professor of Underground Construction & Tunneling and Ph.D. students, respectively, Colorado School of Mines, email mooney@mines.

LIGHTS, CAMERAS, DETECTION & CONNECTION.

MATRIX has a full suite of tunneling support products to make your operation safer and more productive.

Lighting

A full line of industrial-grade LED lighting for mobile equipment and fixed installations. Also visual alert and directional lighting plus audible alarms. MSHA & non-MSHA.

Camera Systems

Several options for machine-mounted cameras or video monitoring. MSHA & non-MSHA.

OmniPro Visual Proximity Detection

OmniPro is a camera-based recognition system that helps detect people in the path of mobile equipment. Auto alerts the operator. Workers do not need to wear a signalling device.

N-Connex High-Speed Modular Network

N-Connex is a rugged, “plug and play” fiber optic, Ethernet and Wi-Fi network like no other for tunneling operations. It provides clear, reliable communications via IP phones, smart phones, IP radios, laptops and tags. Lowest cost per installed mile!

Matrix is the authorized sales and service distributor of NLT N-Connex in the United States and Africa.

MATRIX

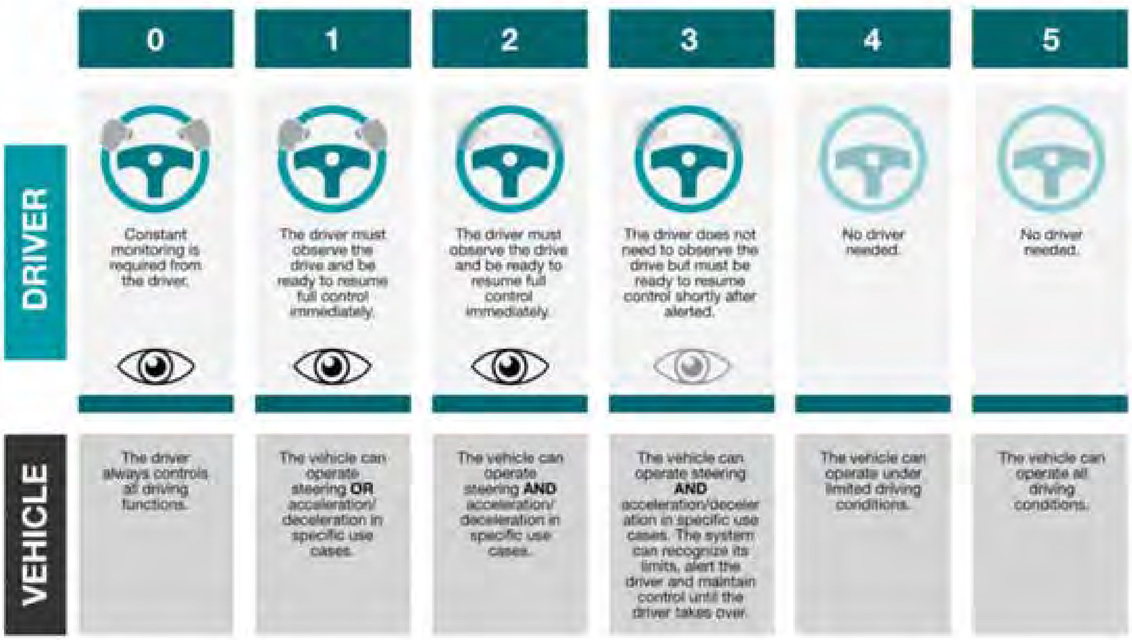
Email: sales@matrixteam.com

Phone: 812.490.1525

www.matrixteam.com

FIG.1

Six levels of autonomous vehicles as defined by the Society of Automotive Engineers (Estl, 2018).



AV sensing. AV technology requires an incredible amount of information that is both gathered from a suite of sensors embedded in the AV and gleaned from dynamic maps hosted on cloud servers. Sensing is the process of identifying all relevant objects and conditions within the relevant field of view that an AV requires. Sensing includes identifying objects (animal, baby stroller, traffic signs/signals, pedestrians, other vehicles) as well as their speeds and trajectories (Yurtsever et al., 2019). Sensing also involves internet of things (IoT)-enabled information (from vehicle to vehicle and from smart signage).

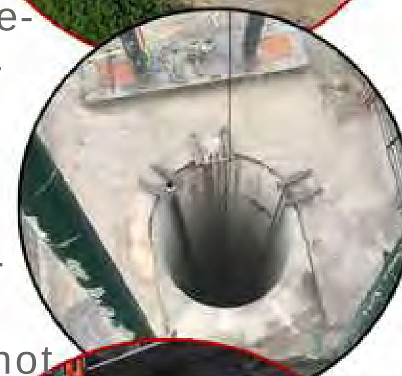
An array of remote sensors outfitted on the AV include optical red, green blue depth (RGBD) cameras, radar, ultrasound and light detecting and ranging (LiDAR) (Rosique et al., 2019). Infrared sensing and ground-penetrating radar (GPR) are also gaining acceptance. This suite of remote-sensing technologies provides redundancy and ideally complete coverage day or night and in all-weather environments (day, night, fog, rain, snow, smoke). A critical component of sensing is identifying objects from remotely sensed information. A radar image, for example, can convey the size, shape, speed and trajectory of an object, but it does not indicate what the object is (Fig. 2). Machine learning, embedded within the technology of computer vision, plays a significant role in object identification.

AV technology also uses high-resolution maps as a quasi-baseline condition for route and motion planning. Such maps include road configurations and current information about traffic, weather-impacted road conditions, construction conditions, etc. These maps are highly dynamic based on real-time measurements of vehicle speed and congestion for traffic forecasting as well as temperature, precipitation, vehicle braking, traction control and windshield wiper use for road condition forecasting (Galanis et al., 2018). Global positioning system (GPS) and inertial measurement units using gyroscopes and accelerometers characterize the position and trajectory of the AV (i.e., AV localization (Fig. 2)).

There are some important sensing similarities and differences with TBM tunneling. The biggest difference lies in remote-sensing technologies. While AVs can use optical, LiDAR, radar and ultrasonic to image the desired field (tens of meters) with the requisite spatial resolution, tunnel-project remote-sensing options are very limited. Geophysical seismic, GPR and electrical resistivity methods have been used with only marginal efficacy to characterize the ground ahead of TBMs (Mooney et al., 2012). We posit, however, that remote sensing is much more important to AVs than it is to autonomous TBMs. Regarding similarities, AVs need to operate at night and in the most adverse weather conditions (rain, snow, fog). Similar objects that are sensed can change (e.g., pedestrian layers of clothing, size of animal, other vehicle model and age). This introduces significant ambiguity and uncertainty. In shield tunneling, the ground conditions also vary spatially.

Despite tremendous advances, AV sensing is not fully capable of enabling level-five AVs. Sensing techniques struggle to identify some objects (e.g., a ball in the road that has led to AVs stopping). Sensing will also be the limiting factor in autonomous EPB shield tunneling. We cannot reliably image the ground ahead of the TBM, and we do not know what is happening in the critical tool gap, cutterhead openings and excavation chamber. These zones of critical operation need to be better sensed.

OUR SHAFT DIVISION



MILLER has the ability to sink shafts conventiona-ly from 16’ diameter and larger and depths of 1,600‘ or greater. We utilize nontraditional mucking methods that give us an edge on both safety and productivity. We own two raise bore machines with the capacity to do shafts as small as 48” diameter with our Atlas Copco 73R and as large as 26’ diameter with the Herrenknecht RBR400 and up to 2,400’ deep. We offer steel lining or cast in place cocrete lining. We also offer pilot hole guidance to ensure tight tolerances are attained on hole deviation for elevators, man and material hoist, or emergency escape hoist applications. A MILLER shaft is not just another hole in the ground, it is an finely crafted structure that the owner can use and be proud of! Please give us the opportunity to do one/another one for you!

AT MILLER, we strive to bring the best value to our customer’s projects. With fair prices, superb service, and outstanding quality, all delivered by an honest hard-working team of professionals. We are commited to seeing that our values are a part of every project that we do. We strive to practice the highest levels of integrity with all persons involved and praise God in every interaction.

please contact us with all your shaft needs!
618.994.4616 l Jake Welch- jwelch@millercontracting.us

FIG.2

Left: Object sensing using camera-measured image (Aryal, 2018). Right: Localization of AV (courtesy of ZME Science, https://www.zmescience.com/science/news-science/self-driving-car-how-it-sees/).

AV planning. The process of planning is the intelligent brain behind AV technology. This is the process undertaken to perform path planning (route optimization/selection) and motion planning (the longitudinal acceleration/braking and lateral steering commands) for the AV. Considerable machine learning is used within the planning process. Path planning determines the route from the starting position to a desired destination. To find the optimal path from all potential routes, traditionally graph-based methods are used, which consider the optimization of some objective value over all paths (e.g., minimal distance). Also, model predictive control can be used to plan for a limited path ahead. Deep learning methods have been recently used for path planning as well. One representative method is imitation learning, which uses the recorded driving experience to learn how human drivers pick driving paths from the camera-observed images. In that case, the model input is convolutional neural network (CNN)-processed camera images and the output is the human-chosen trajectory. Considering TBM automation, route planning is literally not relevant because the design tunnel alignment is prescribed. However, the process of route planning can be applied to other TBM subsystems.

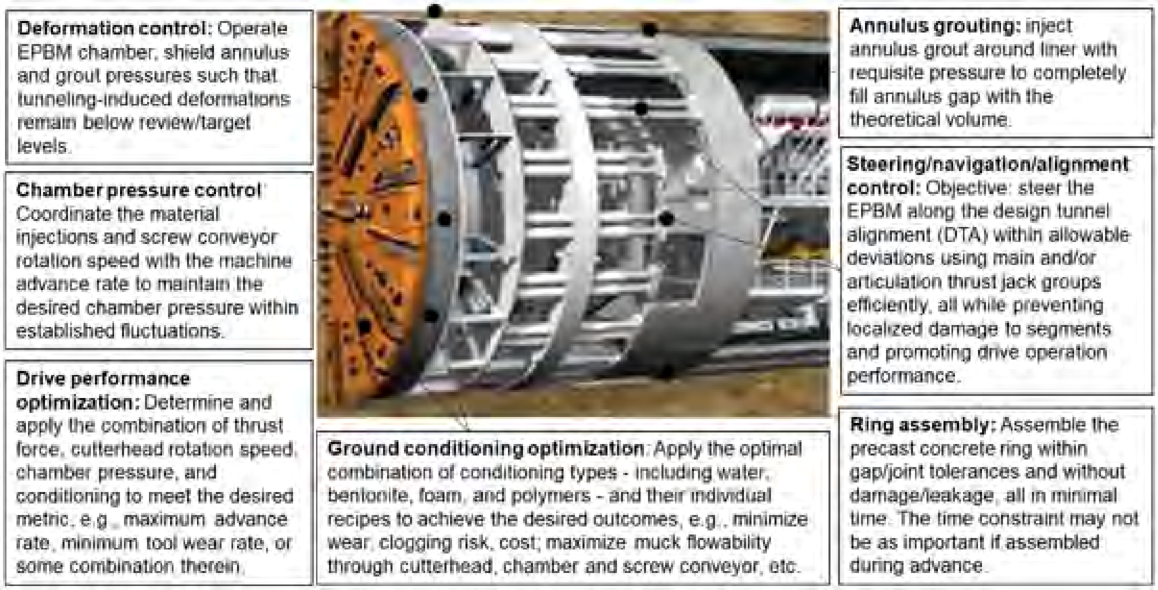
Motion planning to generate the longitudinal acceleration/braking and lateral steering commands for the AV uses physics-based kinematic and dynamics models to determine the action required for the given scenario. In complex cases, machine-learning methods are used to learn the system dynamics, where the past vehicle states are model inputs and the vehicle observations are the outputs. Either physics-based or machine-learning-based models can be used within strategies such as iterative learning control (ILC) and model predictive control (MPC). ILC is simple and computationally lightweight, and is suitable for controlling systems that work in a repetitive mode, such as path tracking, or automatic parking. MPC is a more robust and capable controlling strategy. The central idea of MPC is to calculate the vehicle actions at each time step by minimizing a cost function (error between desired and predicted performance) over a short time horizon, while considering observations, input-output constraints and the system's dynamics given by a process model. The cost function may consider multiple performance goals including static safety (collision avoidance of fixed objects), dynamic safety (avoiding other moving traffic objects), energy efficiency, ride smoothness, etc. The input constraints may include the range limit of steering, brake/acceleration, etc., while the output constraints consist of vehicle speed limit, vehicle cross-track error (deviation) limit, orientation limit and lateral acceleration limit.

AV-motion planning is very relevant and transferrable to TBM automation. In TBM automation, the objective (cost) function also consists of multiple goals (higher advance rate, minimal ground disturbance and deformation, minimal tool wear, minimal alignment deviations). Furthermore, the inputs and outputs, like AVs, are subject to various limitations (thrust force limitation, deviation limitation, torque limitation, chamber pressure limitation, etc.). The TBM dynamics can be modeled based on physics to some extent, but this is uncertain. The ground condition is uncertain due to geotechnical variability, similar to the uncertain traffic environment caused by random driver/pedestrian behavior.

AV action. AV action is concerned with executing the planned operational parameters from the planning stage. The most common feedback controller used in AVs is the proportional-integral-derivative (PID) controller. This seems to also be the case for TBMs. The technology to implement the action phase is straightforward and already developed. As such, little further discussion on action is included in this paper.

FIG.3

Subsystem autonomous operations for EPB shield TBM (image portion courtesy of Herrenknecht).



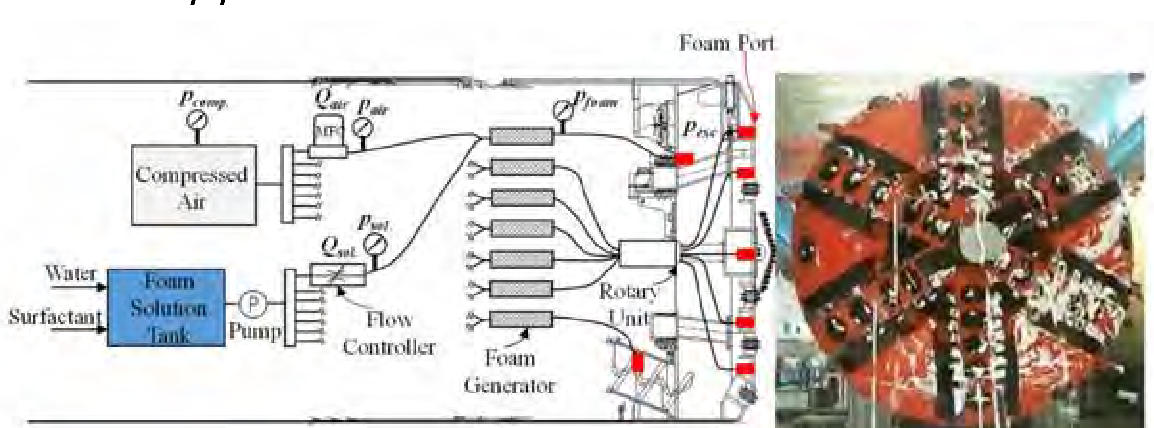
Autonomous EPB shield tunneling

The development of autonomy in subsystem functions has been the mode of operation in AVs and drilling. The same is likely true for EPB shield tunneling. This section summarizes the various subsystem functions in EPB shield tunneling and how they have or will become more autonomous. Seven subsystem autonomous functions are illustrated in Fig. 3. None of these subsystems are mutually exclusive; they are all interrelated. As such, the optimization of parameters within a subsystem is constrained and a system optimization framework is required. Of the subsystems illustrated in Fig. 3, annulus grouting, steering and ring erection have become semi- or fully automated and will not be described due to page limitations. The development of ground conditioning optimization and drive-performance optimization subsystems are detailed using the sensing–planning–action autonomous framework.

Ground-conditioning optimization. Ground conditioning (Fig. 4) is applied to help transform the in situ ground (soil, rock) into a workable medium possessing a consistency that can be used to smoothly balance the water and earth pressure at the face, dissipate that pressure through the screw conveyor, minimize wear and energy required to process, and make for efficient muck passage through the cutterhead, excavation chamber, screw and disposal system (conveyor belt, buckets, truck transport, etc.). There are considerable nuances within this broader goal that depend on ground type. For example, clays and shale present a clogging risk that conditioning must mitigate. Cohesionless sands present ground-water inflow risk and abrasivity that conditioning should mitigate. To this end, there is a suite of ideal conditioned soil

FIG.4

Foam generation and delivery system on a metro-size EPBM.



parameters that can be defined depending on the ground type. These include slump, permeability, shear strength, compressibility and viscosity for cohesionless sands, and consistency index, viscosity and adhesion for cohesive clays. However, there are numerous optimal conditioning inputs that vary ambiguously across soil types, including the type of conditioning agent, liquid quantity, foam injection ratio, foam expansion ratio and concentration. In addition, the configuration and size of the cutterhead, excavation chamber and screw conveyor play a significant role in the conditioned muck properties.

Sensing. Ideally, we wish to know the properties of the conditioned state in the tool gap, cutterhead windows, excavation chamber and screw conveyor. These properties include shear strength, compressibility and adhesion. In current EPBM tunneling, these properties are not directly measured in the desired locations. Instead, we rely on indirect measurements, including cutterhead thrust force and torque, chamber pressure fluctuation and gradient from crown to invert, screw conveyor torque and pressure gradient and measured properties from belt samples (stickiness, slump, density, shear strength). Sensing within future EPBM may involve multiphysics belt muck scanning, direct sensors (e.g., rheometer, embedded in the tool gap, chamber and screw conveyor).

Planning. Measurable criteria are needed, including:

- Chamber pressure fluctuation (dp/dx where p = pressure and x = longitudinal/advance position), chamber pressure gradient (dp/dz where z is the vertical position), and screw pressure gradient (dp/dL where L is length along screw conveyor).
- Belt muck properties (density, adhesion, shear strength under a desired pressure, slump).
- Cutterhead torque, cutterhead thrust force.

The relationships between desired outcomes and measured outcomes must be developed as a function of conditioning variables (e.g., form of conditioning, location of conditioning, foam injection ratio (FIR), foam expansion ratio (FER), water injection ratio, bentonite injection ratio). Such relationships can be developed from statistical models, machine learning models or physical models. With measurements and desired outcomes, the recommended adjustments to the conditioning variables to move from current outcomes to desired outcomes can be computed using the established relationships.

The mathematical framework for computing recommended adjustments can come from physics- and mechanics-based models (e.g., Yu et al., 2017) or from machine learning-based models (Mooney et al., 2018). With the former, the chamber pressure response is predicted based on TBM operations and conditioning inputs. Given the complexity of the EPBM/ground/conditioning interaction, the modeled and measured outcomes are likely different. To this end, the model must be calibrated on the fly. Machine-learning models, by design, learn while doing and therefore will continuously expand knowledge of conditioning as data are collected. Where there are co-dependent relationships that sometimes may conflict, a weighting system is implemented. Examples of this include a desire to reduce cutterhead torque to some set point and a desire to maintain a set-point chamber pressure gradient. These two outcomes may invoke different conditioning actions.

Action. The recommended adjustments are implemented via the EPB shield's PLC that sends analog signals to the system actuators to adjust flow rates as prescribed (e.g., flow controllers in Fig. 4). The array of actions include different recommendations for cutterhead, excavation chamber and screw conveyor conditioning. A feedback control loop is used to implement the continuous loop of sensing, planning and action. The loop is typically completed on a time interval of 5-10 minutes for soil conditioning given the latent response to action. Autonomous soil-conditioning optimization (McLane, 2014) can also incorporate geotechnical information (e.g., both from the ground model built from geotechnical site investigation data and from EPBM prediction of the ground type using deep learning).

Drive-performance optimization. Tunneling performance is determined by multiple factors, such as machine advance rate, alignment deviations, ground settlement/disturbance, material consumption and tool wear. Depending on the specific scenario, their priorities vary. For example, when tunneling in a deformation sensitive area, achieving minimal alignment deviation and ground disturbance is critical. Conversely, a project that has experienced significant delays may prioritize high advance rate. When the performance metric is specified, optimizing drive performance is an optimal control problem, in which the machine operations are adjusted to achieve the best expected performance. To this end, models relating operations with performance (Mokhtari, et al., 2020) are needed, either derived from physics or via statistical learning. In addition, given the limited machine capacity, as well as other coupled reactions that are subject to limitations, feasible machine operations are constrained. Improving drive performance therefore involves solving a constrained, nonconvex optimization problem that is solvable with a heuristic method.

Sensing. Many machine operations and reactions are measured on modern EPB shield machines. For operations, these include the individual thrust and articulation jack forces, cutterhead and screw conveyor rotation speeds, and the material injection rates of foam, bentonite, water and polymer. For machine reactions, advance rate, alignment deviations, chamber pressure and its distribution,

cutterhead torque, screw conveyor torque and pressure are all measured. However, there are still performance metrics that are unrecorded. A major limitation is the lack of sensing in the critical tool gap, cutterhead openings and excavation chamber areas. Further, continuous cutting tool wear is rarely measured on EPB shield machines, making it hard to quantify wear rates under different operations. This can be solved by adding wired or wireless sensors to the cutting bits. Another common issue is the lack of proper sensor calibration (e.g., thrust jacks) and inadequate sampling frequency (e.g., torque measurement), both impacting the data quality and their usage for downstream processing.

Planning. To perform optimal control, both the performance objective and all coupled machine reactions are modeled. Take the advance rate maximization as an example, its optimal control formulation is given as follows:

$$\max_X \widehat{AR} = f(F_i, \omega, \hat{p}, \hat{T})$$

subject to

$$\begin{aligned}
&p_{min} \le \hat{p} \le p_{max} && \hat{p} = f(\omega_s, Q_{air}, Q_{sol}, \widehat{AR}, p^{t-1}) \\
&\hat{T} \le T_{max} && \hat{T} = f(F_i, \omega, \widehat{AR}, \hat{p}) \\
&FIR_{min} \le FIR \le FIR_{max} && FIR = f(Q_{air}, Q_{sol}, \widehat{AR}, \hat{p}) \\
&FER_{min} \le FER \le FER_{max} && FER = f(Q_{air}, Q_{sol}) \\
&F_{i,min} \le F_i \le \alpha F_{i,max} && \\
&\omega_{min} \le \omega \le \omega_{max} && \\
&\omega_{s,min} \le \omega_s \le \omega_{s,max} &&
\end{aligned}$$

where EPB shield operations $\boldsymbol{X}$ include the individual thrust jack forces F_i, cutterhead rotation speed ω, screw conveyor rotation speed ω_s, as well as foam air and solution injection rates Q_{air}, Q_{sol}. $\widehat{AR}$ is the estimated advance rate to maximize and is a function of F_i, ω, estimated cutterhead torque $\hat{T}$ and estimated chamber pressure $\hat{p}$. Given the challenge of physics-based modeling, $\widehat{AR}$ can be obtained with machine learning using data recorded on previous rings as well as geotechnical information (Mooney et al., 2018). In addition, $\hat{T}$ and $\hat{p}$ are explicitly modeled and considered as optimization constraints. For example, the estimated value of chamber pressure $\hat{p}$ should be within the tunneling face pressure bounds $[p_{min}, p_{max}]$. Estimated cutterhead torque $\hat{T}$ must not exceed the capacity of the torque motors. Cutterhead torque can be estimated using physics-based models (Godinez et al., 2015). A similar situation applies to the *FIR* and *FER*. Finally, individual thrust jack force F_i, cutterhead rotation speed ω, and screw conveyor rotation speed ω_s all have their own mechanical limits set by interlocks and are all treated as constraints. The objective function and the constraints are nonconvex; therefore, solving the optimization above requires heuristic strategies such as particle swarm optimization.

Action. Formulations like the one above can be deployed for EPBM shield optimal control, though issues such as computation efficiency need to be addressed properly to

FIG.5

Diagram showing the performance of the AR model, learned using support vector regression. The training was conducted on the first 20 rings (#1001-1020) and was then tested on the following 20 rings.

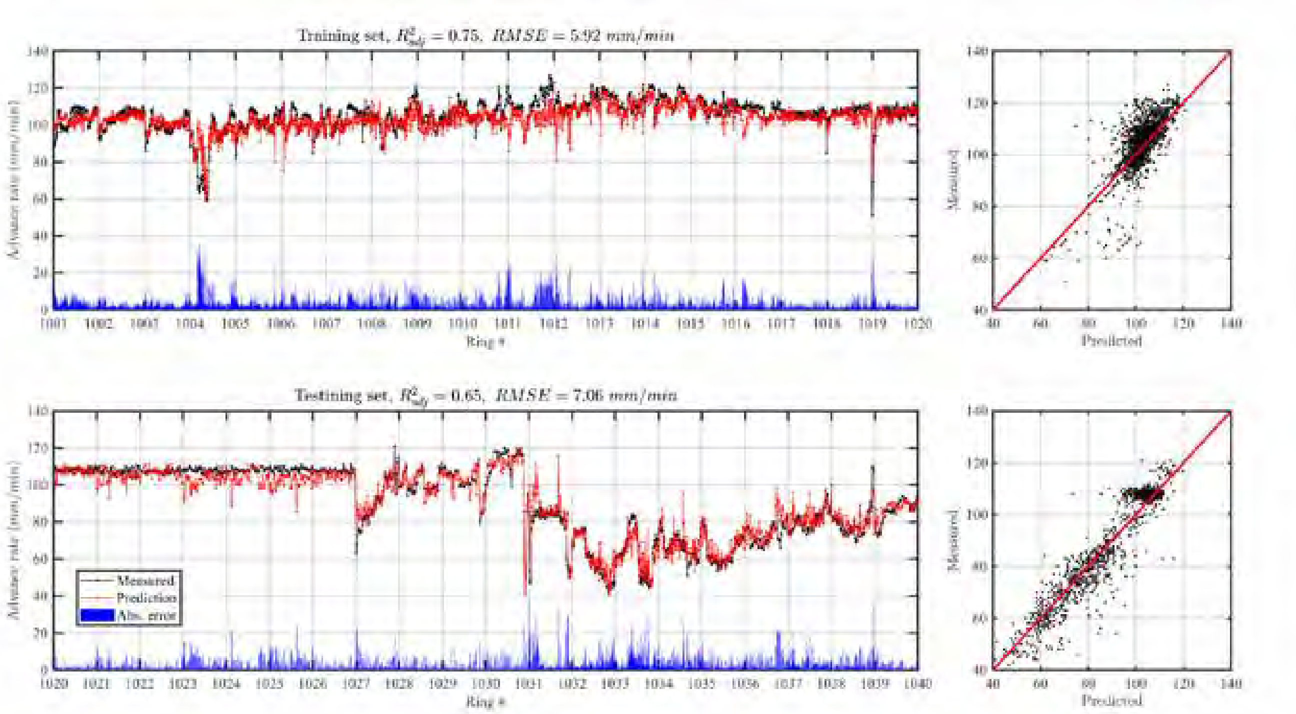
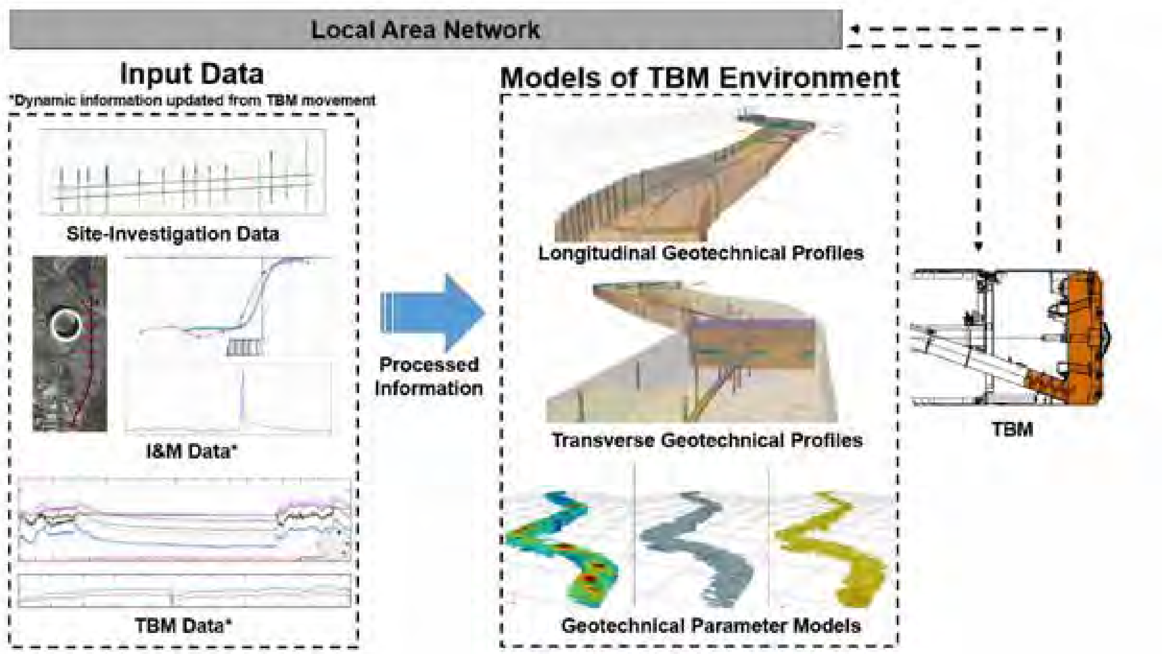


FIG.6

Schematic layout of the environment perception framework for autonomous TBM tunneling.



yield the control in real time. Figure 5 presents one example where a predictive model, $\widehat{AR} = f(F_i, \omega, \hat{p}, \hat{T})$ was trained with a support vector regression model using the previous 20 rings worth of EPB shield data. The model performance is good, with $R^2 = 0.75$ and $RMSE = 5.92$ mm/min. The model, in this example, was then used to predict performance over the subsequent 20 rings using the EPB shield inputs actually adopted. As shown in Fig. 5, its performance is still acceptable, with an $R^2 = 0.65$ and $RMSE = 7.06$ mm/min. In addition to this example, the model provides as output a suite of input parameters to maximize AR. The input parameters are implemented via PID control on the EPB TBM.

It is worth noting that there are myriad supporting operations as well as logistics that must be adequately functioning to enable autonomous operations. These include material batching (e.g., grout, bentonite, conditioners, consumables resupply, umbilical extensions, segment transport and mucking operations, to name a few). Some, if not all, of these can be made autonomous. Ideally, these operations are taken off the tunneling critical path.

Geotech environment perception

The ground plays a significant role in autonomous TBM tunneling. This environment is akin to the road network and spatial obstacle array in the area around an AV. A major concern and constraint for autonomous TBM tunneling is the fact that the spatial characterization of ground conditions along and above a tunnel project alignment is highly uncertain. A related uncertainty lies in the behavior of the ground (e.g., uncertainty in shear strength, deformation and excess pore water-pressure generation). Efforts to advance autonomous TBM tunneling, therefore, must implement ways to correctly capture spatial geotechnical uncertainty and use data to continuously update geotechnical conditions. This updating of geotechnical conditions is similar to updating road conditions performed in concert with AV technology (described earlier).

Updating the ground condition can be realized by using geostatistical models, machine-learning models or a combination of the two. Geostatistical models enable a spatial estimation of the geological-geotechnical conditions at unsampled locations and help quantify spatial uncertainty. A 3D rendering of the geological-geotechnical environment, developed using the geotechnical site investigation and associated laboratory testing results, will be fed into the local area network (LAN) for the autonomous TBM to use. TBM operation parameters can be used to estimate the as-encountered ground conditions using machine-learning models. Additionally, instrumentation and monitoring (I&M) data can be back-analyzed using suitable machine-learning algorithms and physics models to estimate the ground conditions within the zone of influence. Integrating the prior-to-construction estimates of geological-geotechnical conditions from geostatistical modeling and preposterior estimates from TBM and I&M data can aid in continuously updating the geological-geotechnical environment along the tunnel alignment. The process can enable TBMs to gain updated knowledge of the excavation environment. Figure 6 presents a general environment perception framework for autonomous TBM tunneling.

Conclusions

Autonomous vehicles (AVs) provide a compelling road map for autonomous TBM advancement. With a well-thought-out structure for autonomy and AVs currently at level 3 (of 6), AV technology development has been remarkable, and fully autonomous AVs are anticipated within the next decade. Using the AV framework of sensing (perception)–planning–action (control), this paper has described the various EPM TBM subsystems that are currently partially automated or can become autonomous in the future. As with AVs, the biggest hurdle to autonomous TBM tunneling is sensing, particularly in the critical areas immediately ahead of the cutterhead, at the cutterhead and through the excavation chamber and screw conveyor. Advances in the sensing of these areas is required to drive autonomous TBM technology.

Nontechnical aspects of AVs and autonomous TBM tunneling include human trust, liability and regulation. Volvo, for example, has stated it will accept all liability with its AVs. The liability associated with autonomous TBM tunneling will be a significant barrier (e.g., Who will accept this risk and how will this liability be underwritten?). Owner acceptance and regulation will also require development (e.g., Under what conditions will owners permit autonomous TBM operations in urban environments?). ■

References

Aryal, M., 2018. Object Detection, Classification, and Tracking for Autonomous Vehicle.

Camus, T., Moubarak, S., 2015. Maintenance robotics in TBM tunnelling, ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction. IAARC Publications, p. 1.

de Wardt, J., Chapman, C.D., Behounek, M., 2012. Well Construction Automation-Preparing for the Big Jump.

de Wardt, J.P., Sheridan, T.B., DiFiore, A., 2016. Human Systems Integration: Key Enabler for Improved Driller Performance and Successful Automation Application, IADC/SPE Drilling Conference and Exhibition. Society of Petroleum Engineers.

Estl, H., 2018. How ADAS Is Paving the Way for Autonomous Driving (https://www.5gtechnologyworld.com/how-adas-is-paving-the-way-for-autonomous-driving/).

Etherington, D,. 2019. Over 1,400 self-driving vehicles are now in testing by 80+ companies across the US. Retrieved from https://techcrunch.com/2019/06/11/over-1400-self-driving-vehicles-are-now-in-testing-by-80-companies-across-the-u-s/

Galanis, I., Gurunathan, P., Burkard, D., Anagnostopoulos, I., 2018. Weather-based road condition estimation in the era of Internet-of-Vehicles (IoV), 2018 IEEE International Symposium on Circuits and Systems (ISCAS). IEEE, pp. 1-5.

Godinez, R., Yu, H., Mooney, M., Gharahbagh, E.A., Frank, G., 2015. Earth Pressure Balance Machine Cutterhead Torque Modeling: Learning from Machine Data, Rapid excavation and tunneling conference, New Orleans.

Insurance Information Institute, 2019. Facts + Statistics: Highway safety (https://www.iii.org/fact-statistic/facts-statistics-highway-safety).

Jacobs, T., 2015. Automated Drilling Technologies Showing Promise. SPE-0615-0050-JPT 67, 50-55.

Kinik, K., Gumus, F., Osayande, N., 2014. A case study: first field application of fully automated kick detection and control by MPD system in western Canada, SPE/IADC Managed Pressure Drilling & Underbalanced Operations Conference & Exhibition. Society of Petroleum Engineers.

Kockelman, et al., 2017. An assessment of autonomous vehicles: traffic impacts and infrastructure needs - final report. Report FHWA/TX-17/0-6847-1, 182 p.

Lopes, L., Miklovicz, T., Bakker, E., Milosevic, Z., 2018. The benefits and challenges of robotics in the mineral raw materials sector-an overview, 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, pp. 1507-1512.

Martin, D., 1990. JAPANESE ROBOT CAN ERECT SEGMENTS. Tunnels & Tunnelling International 22.

McLane, R., 2014. Automatic Soil Conditioning Through Clay. North American Tunneling: 2014 Proceedings.

Mokhtari, S., Navidi, W., and Mooney, M.A. White Box Regression (Elastic Net) Modeling of Earth Pressure Balance Shield Machine Advance Rate, Automation in Construction, 2020, 115(103208), https://doi.org/10.1016/j.autcon.2020.103208.

Mooney, M., Yu, H., Mokhtari, S., Zhang, X., Zhou, X., Alavi, E., Smiley, L., Hodder, W., 2018. EPB TBM Performance Prediction on the University Link U230 Project. North American Tunneling 2018 Proceedings.

Mooney, M.A., Walter, B., Frenzel, C., 2012. Real-time tunnel boring machine monitoring: A state of the art review. North American Tunnelling, 2012 Proceedings, 73-81.

Rogers, W.P., Kahraman, M.M., Drews, F.A., Powell, K., Haight, J.M., Wang, Y., Baxla, K., Sobalkar, M., 2019. Automation in the Mining Industry: Review of Technology, Systems, Human Factors, and Political Risk. Mining, Metallurgy & Exploration, 1-25.

Rosique, F., Navarro, P.J., Fernández, C., Padilla, A., 2019. A systematic review of perception system and simulators for autonomous vehicles research. Sensors 19, 648.

Schwob, A., Guedon, F., Combe, B., Lockhart, T., 2019. Tuen Mun–Chek Lap Kok Link in Hong Kong–Innovative solutions for construction of an outstanding Subsea Tunnel, Tunnels and Underground Cities. Engineering and Innovation Meet Archaeology, Architecture and Art. CRC Press, pp. 3086-3096.

Shimz Corporation, 2018. AI-based Support System Developed for Shield Excavation Planning.

Shirlaw, J.N., Richards, D.P., Ramond, P., Longchamp, P., 2004. Recent experience in automatic tail void grouting with soft ground tunnel boring machines, Proceedings of the ITA-AITES World Tunnel Congress, Singapore, pp. 22-27.

Wu, C., Liu, X.-J., Wang, L.-P., Wang, J., 2011. Dimension optimization of an orientation fine-tuning manipulator for segment assembly robots in shield tunneling machines. Automation in Construction 20, 353-359.

Yu, H., Mooney, M., Bezuijen, A., 2017. A Simplified Chamber Pressure Model for EPB TBM Tunneling in Granular Soil, in: Jr., A.N., Jr., M.O.C. (Eds.), 9th International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, Sao Paulo.

Yurtsever, E., Lambert, J., Carballo, A., Takeda, K., 2019. A Survey of Autonomous Driving: Common Practices and Emerging Technologies. arXiv preprint arXiv:1906.05113.

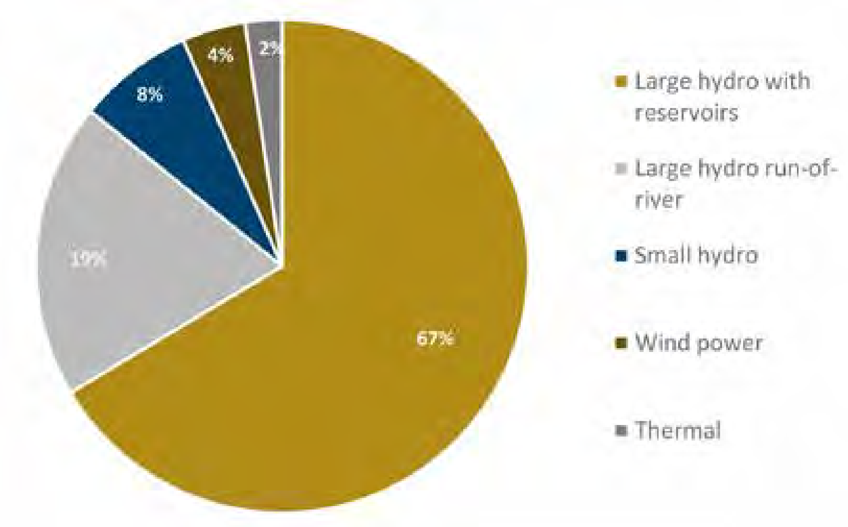
Tunnel-boring machines for Norwegian small hydropower projects

Norway has a long history in hydropower and has a yearly production of 135 terawatt hours (TWh) distributed across more than 1,600 hydroelectric power plants. This production capacity covers more than 94 percent of the total electricity usage in the country. The vast majority of power plants in Norway were built before 1990, and more than 200 km (124 miles) of associated tunnels were excavated by tunnel-boring machines (TBM) during Norway's big hydropower era stretching from the late 1960s to the early 1990s.

As a larger degree of Norwegian rivers, streams and waterfalls were tamed for hydropower, public resistance grew against hydropower projects. In the mid-1990s, then-Norwegian Prime Minister Jens Stoltenberg declared that the era of big hydropower construction was over.

FIG.1

Power production by percentage in Norway (Normal year, OED, 2019).



Nevertheless, the Norwegian topography and water resources still represented a major potential for hydropower, especially if a solution with less impact on the environment could be found. One of these solutions included small hydropower projects, defined as hydropower plants with an installed capacity of less than 10 MW.

This article addresses why small hydropower projects are a great way of generating electrical energy and why mechanized tunneling is a beneficial way of making them.

Small hydropower projects and why they matter. There are currently more than 1,300 small hydropower plants operating in Norway with an installed yearly production of 11 TWh. The small hydro share of the total power production is currently around 11 percent (Fig.1).

The local impact on nature of these small projects is generally lower than larger hydropower projects, construction is cost efficient and quicker, and the initial investment required is lower. The widespread availability of locations where these projects can be built also offers a great distribution of value generation across all parts of the country (Smakraftforeninga, 2016).

Sindre Log, Rune Skjevdal and Tobias Anderson

Sindre Log, member UCA of SME, is civil engineer - product manager/cutters, The Robbins Company and Rune Skjevdal and Tobias Anderson are chief executive officer and TBM chief, respectively, NGK Boring, email logsindre@robbinstbm.com.

Construction of small hydropower projects. A significant number of the existing small hydroelectric power projects (SHEPPs) had been constructed either with pipes on the surface or by trenching. In recent years it has been a general trend that larger parts of these SHEPPs are built in tunnels, either due to the topography or to reduce the environmental impact even more.

In small hydroelectric projects that require an underground waterway, the tunnel is usually built by one of the following methods:

- Trenching.
- Drill and blast tunneling.
- Raise drilling.
- Directional drilling.
- TBM boring.

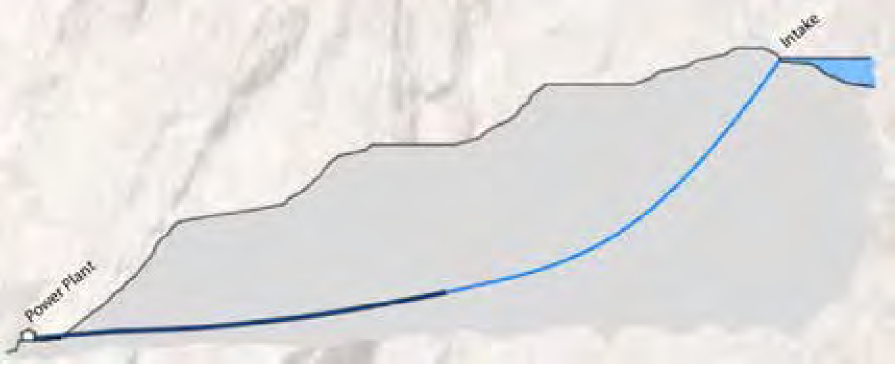
As a rule, trenching is the most cost-efficient solution for such projects. However, in many cases the topography and nature of the projects do not allow for trenching. If a tunnel is needed, the other options have historically been between drill and blast tunneling, raise drilling or

FIG.2

Typical small hydro layout (Norhard.no).

FIG.3

Typical small hydro layout (Norhard.no).



directional drilling or a combination of those methods.

The SHEPPs that consist of a tunnel often have some physical constraints that limit the construction method:

1. There is naturally a big elevation difference between the tunnel portals.
2. There is generally as much overburden as is practically possible toward the downstream portal to avoid challenging geology, hydraulic fracking and hydraulic jacking, and to lower costs.

These limitations mean that the vertical profile of a SHEPP tunnel is often similar to Fig. 2, with limited inclination in the downstream portal and high inclination toward the upstream portal.

The traditional way of constructing such projects has been to drill and blast the flat part and raise bore the incline. A concrete plug is installed where hydraulic jacking forces are lower than the minor principle stress in the surrounding rock and further through a pipe in the tunnel toward the powerhouse. The most common blasted cross section is between 16 and 25 m² (175 and 269 sq ft) due to limitations in the available equipment as well as the challenges of excavating efficiently with drill and blast at diameters smaller than 16 m² (175 sq ft). If the tunnel was to be excavated with other methods, a profile like Fig. 3 would be typical.

The alternative to the conventional method has been directional drilling performed with a heavily customized directional drilling rig such as that devised by Norwegian company Norhard AS. The Norhard drilling rig consists of a pilot tri-con bit for drilling with carbide raise drill cutters to ream up the diameter of about 0.7 m (2.2 ft). The hole can then be reamed up with several drillings up to a diameter of 1.5 m (5 ft). The drill string is powered by a nonrotational drill string from the outside (Fig. 4).

As the SHEPPs have become increasingly complex, TBMs have been introduced on several projects in Norway in recent years as an excavation method that has its own unique benefits.

Benefits of mechanized tunneling for hydropower. Mechanized tunneling offers some significant advantages on unlined hydroelectric power projects:

- Reduction of needed cross section due to lower surface roughness.
- Better tunnel quality, resulting in less rock support and lower lifecycle costs.
- Less impact on the environment.
- Reduction of tunnel construction time.

Due to the lower surface roughness of the tunnel wall in a mechanically excavated tunnel, the water flows better and the needed theoretical cross section can be reduced by 40-60 percent. A more detailed graph is given in Fig. 5.

The more efficient water flow, and the capability of using the tunnel as the water-carrying pipe, reduces the need for excavated material significantly. This means less excavated material needs to be removed and stored and is also economically advantageous.

Less rock support is required in general in mechanically excavated tunnels, and because of the better tunnel quality, there are lower lifecycle costs to maintain the tunnel. Mechanized tunneling also disturbs the environment far less than drill and blast operations. The empirical data from TBM-excavated hydropower projects in Norway support these points. Results show that there is a reduction in installed rock support of between 40 and 90 percent when boring a tunnel with a TBM instead of blasting it. The theory behind this result is that a lot of the rock support in blasted tunnels with small cross sections is installed to stabilize rock that has been damaged by the blasting. The TBM-bored tunnel walls are less damaged, which also increases tunnel quality, ultimately leading to lower maintenance cost of the tunnels and longer tunnel life. Also, the smaller

FIG.4

Norhard breakthrough with pilot hole on Grytendal project (NGK, 2019).

FIG.5

Reduction of theoretical cross section with mechanized tunneling (Log, modified based on NTNU, 1998).

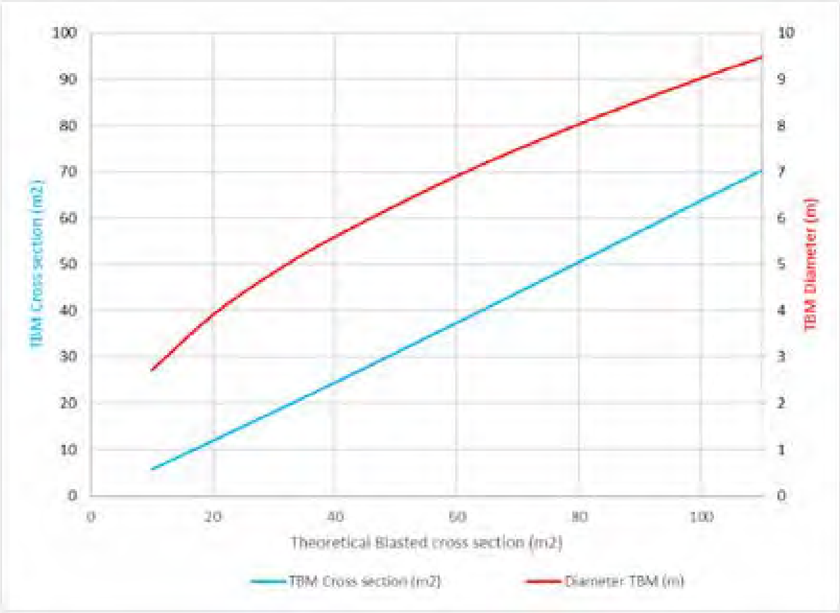


FIG.6

Double Shield Rockhead at Holen SHEPP. (Photo: Endre Hilleren)

tunnel dimension and the circularity of the hole increases the stability of the rock and decreases the need for rock support.

Excavation with TBMs also offers several environmental advantages. The TBM and muck haulage are typically run on 100 percent electric power from the grid, which in Norway consists of 94 percent renewable energy. In addition to the already-mentioned environmental aspects that include reduced excavated material, mechanized tunneling eliminates the risk of nitrous run-off and plastic waste that are present in drill and blast material deposits.

TBMs for small hydropower

For the past 10 years there has been interest from owners, contractors and the government to develop TBM solutions for some of the upcoming SHEPPs in Norway. From a TBM design perspective, there are some special challenges of the Norwegian SHEPPs:

1. The theoretically needed cross section is usually very small and requires TBMs smaller than 3 m (10 ft).
2. Norwegian rock is often extremely hard.
3. The geometry of the projects is often challenging, with the tunnels often containing high inclines, combined with vertical and horizontal curvature.
4. Some of the projects have limited space on site and no road access at the upstream portal.
5. The length of the tunnel is typically between 500 and 3,000 m (1,640 and 9,800 ft).
6. The budgets for these projects are often extremely limited.

These challenges require a unique TBM design:

1. The TBM needs to be small but still equipped with sufficient cutter sizes to efficiently break the rock.
2. The TBM cutter diameters must be as large as possible and the highest quality disc ring material must be used to reduce cutter changes due to the limited space.
3. The machine needs to be able to negotiate steep inclines and the transitions between inclines.
4. The TBM needs to be able to backtrack through the tunnel.
5. The TBM must be optimized to be used on several projects with limited service time in between.
6. The TBM package needs to be economically viable.

FIG.7

Breakthough at Holen SHEPP (Photo: Hardanger Maskin AS).

7. The TBM might need to be able to launch from a limited space area.

This led Robbins to develop two separate solutions for the Norwegian hydro projects. One was based on small boring units (SBU), a line of trenchless boring equipment and machinery typically 2 m (6.6 ft) or smaller in diameter, while the other used more standard TBM technology.

Small-diameter design: Holen hydropower. The first tunneling machine for SHEPPs was ordered by Hardanger Maskin AS, for the project Holen Hydropower owned by Smaakraft AS in early 2018.

Robbins developed a new solution for the project using well-proven SBU technology. The Double Shield Rockhead (SBU-RHDS) provided for the tunnel includes 360 cm (14 in.)-diameter cutters and is capable of self-propelled excavation using a gripper system.

The novel 2 m (78 in.)-diameter machine is equipped with unique features that allow it to drill at a steep incline, including electric power, modified oil and lubrication systems and a fail-safe safety gripper (secondary gripper), as well as a water-based spoil removal system, developed by the contractor (Fig. 6).

Due to local terrain, the tunnels had a small launch area of 4 × 10 m (13 × 33 ft) and the tunnel slope on the first 640 m (2,100 ft)-long drive ranged from a slight upward tilt to 45 degrees at the breakthrough.

The Rockhead launched in July 2018 with Robbins Field Service onsite assisting Hardanger Maskin AS with assembly, setup and launch of the equipment. As tunneling began, the slope was near horizontal, but as the tunnel got steeper, the special safety gripper system came into use. The safety gripper system was designed with interlocks to ensure primary grippers were never released while the safety grippers were engaged and with an additional safety mechanism that allowed for mechanical locking in the event that hydraulic pressure was lost.

While the excavation rate of the machine was good, the novel design experienced some reliability issues during tunneling in the hard granite. Despite the challenges, the machine completed a daring hole-through at a steep 45-degree incline on Jan. 1, 2019. It has since been relaunched to bore its second 640 m (2,100 ft)-long tunnel, where the design continues to be fine-tuned (Fig. 7).

Unique TBM and conveyor solutions: Salvasskardelva SHEPP. The other solution, based on more standard TBM technology, came into use in the summer of 2019. Robbins supplied the 2.8 m (10 ft)-diameter specialized main-beam TBM, Snøhvit, to Norsk Grønnkraft to use on several of their hydroelectric tunnels. In addition to investing in a TBM, Norsk Grønnkraft also started a specialized contracting company, NGK Boring, that entered into a cooperation with Entreprenørservice AS to construct the tunnels.

The first tunnel, the 2.8 km (1.7 mile)-long Salvasskardelva SHEPP located in Bardu, Norway, has a modest positive gradient of 5.2 percent. To combat boring on a grade, the small main-beam TBM was designed for adaptability with an option to add a safety gripper on future tunnels for boring at high inclines.

The TBM is equipped with nineteen 432-mm (17-in.) cutters with a load rating of 267 kN each (Fig. 8). The 2.8 m (1.7 ft)-diameter cutterhead is powered by four 210-kW variable frequency drives (VFDs).

A continuous conveyor was provided for muck removal, making it the smallest conveyor belt Robbins has ever provided. The 450 mm (18 in.)-wide conveyor belt will need to travel through curves, which begin at the 650-m (2,132-ft) mark at Salvasskardelva. The structure was designed to minimize muck spillage in curves despite its narrow width and is within its design limits. The small jobsite also required the use of a double-stack belt storage cassette standing 5 m (16 ft) tall. The unique system is planned to be reused at each of the tunnel sites.

NGK and Robbins worked together during the design period to design a launch frame instead of excavating a starter tunnel, which allowed the machine to advance until it was well enough into the tunnel to grip the tunnel walls. The launch frame is planned for reuse on subsequent tunnels.

As of December 2019, the TBM had surpassed the 1,300-m (4,265-ft) mark, and the machine was excavating

FIG.8

Crown-mounted conveyor at Salvasskardelva.

well in mica gneiss and schist rock, achieving rates above 100 mm (3.9 in.) per minute.

Small-diameter hydro tunneling looks poised to continue making a big impact in Norway. A third TBM, a 2.6 m (8.5 ft)-diameter Robbins Double Shield TBM with a safety gripper, began excavation in the winter of 2019 at the Tokagjelet SHEPP. The alignment of the 2.2 km (1.4 mile)-long tunnel will increase gradually from near-horizontal to a 45-degree incline.

Conclusions

Hydroelectric power generation has historically required high investments and mountainous topography with water in abundance. Unfortunately, the sizes and complexity of traditional hydropower projects also tended to have a negative impact on the surrounding environment.

The small hydro project approach introduces an opportunity to construct renewable energy with limited investment and limited negative consequences on the local environment. Given the increasing interest in small hydro tunnels and the fine-tuning of effective designs for rock tunnels at steep inclines, there is a huge potential for continued projects in Norway and in other locations such as the United States. Renewable energy with a reduced initial investment and construction time could become essential wherever the terrain is hilly or mountainous and water features abound.

Infrastructure spending, particularly on water tunnels, is on the rise in the United States, and it is believed that there is a tremendous potential for small hydropower projects in North America. Small hydropower is likely to become more popular as it offers the best of several worlds. It is an environmentally friendly way of generating power, is less taxing on natural resources and is cost-effective and quick to implement. It does not require the large waterfalls and high mountains that big hydropower schemes require. ■

References

SSB (2016). Kryssløpstabeller - ESA Questionnaire 1850 - Symmetric input-output table for domestic production (industry*industry). Tilgjengelig på https://ssb.no/en/nasjonalregnskap-ogkonjunkturer/tables/supply-and-use-and-input-output

Småkraftforeninga (2016).“Samfunnsnytte av småkraft”. Thema Consulting group

NTNU (1998). NTNU-Anleggsdrift: Project Report 1A-98 HARD ROCK TUNNEL BORING Design and Construction.

Norhard (2019). Pictures from Norhard.no

NGK (2019). Picture courtesy of Norsk Grønnkraft

Work on Hampton Roads Bridge-Tunnel project gets underway

Work on the $3.8 billion Hampton Roads Bridge-Tunnel in Hampton Roads, VA is underway and has not been halted by the COVID-19 pandemic.

When the project is completed in 2025, there will be two, new two-lane tunnels in addition to the existing ones. Interstate 64 will also be widened on both sides of the tunnel.

Paula Miller, a spokeswoman for the project, said crews are working on the early stages of the project and are putting up new power poles and fixing existing ones. This is to prepare for more electrical current to power a tunnel-boring machine (TBM).

The Virginia Department of Transportation (VDOT) officials said it's the second-largest TBM used in the United States and is scheduled to launch from the South Island in about a year and a half.

The Hampton Roads Bridge-Tunnel expansion is projected to bolster the economic competitiveness of the Hampton Roads region with more than $4.6 billion in investments and a projected 28,000 new jobs over the life of the project.

"The largest project in VDOT history, this expansion will address some of our most pressing transportation challenges and unlock opportunity for families, military personnel and businesses, not only in the Hampton Roads region but across the Commonwealth," said Virginia Gov. Ralph Northam. "These agreements are a culmination of the diligent work and extensive negotiations by our dedicated teams over the past year to deliver significant improvements to reduce daily congestion, increase safety, and enhance connectivity throughout this key corridor."

The Hampton Roads Transportation Accountability Commission, a regional financing entity, will pay for $3.56 billion of the project cost. That money comes from an existing regional surcharge on fuel taxes and sales taxes.

VDOT will kick in $200 million from its so-called "Smart Scale" financing program and $109 million from a special fund for critical projects, to be used to replace trestles that carry the roadway on the Norfolk side of the bridge-tunnel. ■

DERRICK MUD RECYCLING TECHNOLOGY

PATENTED SCREEN SURFACES | COMPLETE SYSTEMS | SOLIDS REMOVAL EQUIPMENT

Civil Construction Applications:

- Horizontal Directional Drilling
- Microtunneling
- Large Diameter Tunneling
- Hydrovac Mud Processing
- Slurry Wall/Foundation Drilling
- Water Well Drilling

DERRICK®

Derrick Equipment Company
15630 Export Plaza Drive
Houston, Texas 77032
Toll Free: (866) DERRICK

Leading-Edge Slurry Separation Solutions

Backed by nearly 70 years of cost-effective solutions, Derrick has manufactured innovative technologies for numerous civil construction applications for over three decades. Derrick's separation technology offers unmatched solids removal performance. Our civil construction solutions are currently used worldwide by companies that require high-efficiency separation and slurry dewatering in environmentally sensitive and urban environments.

Discover more, visit us at www.Derrick.com

First rail tunnel in Sydney Metro project completed

The first rail tunnels of the Sydney Metro City and Southwest project have been completed. The tunnel-boring machine (TBM), named Kathleen, arrived north of the harbor on March 18, breaking through a wall of sandstone.

The TBM dug two 885 m (2,900 ft)-long tunnels from Barangaroo to Blues Point. The second tunnel was completed in two months, a month faster than the first due to the lessons learned, such as modifying the cutterhead and changing tunneling processes to better deal with the clay material at the bottom of the harbor.

TBM Kathleen dug through about 175 kt (193,000 st) of sandstone, clay and marine sediments for the two harbor tunnels, which are about 40 m (131 ft) below sea level at their deepest point.

Five TBMs working on the project completed 31 km (19 miles) of fully lined tunnels in 17 months.

When completed in 2024, the Sydney City and Southwest metro line will be integrated as a single line with the Tallawong-Chatswood Northwest metro line, which opened in May 2019.

The extension includes a 15-km (9.3-mile) greenfield line with seven new stations, along with the upgrade of the existing suburban line to metro standards, covering an additional 13 km (8 miles) of track and 11 existing stations. The project also includes expansion of the current Sydney Metro Trains Facility at Rouse Hill and a new depot at Sydenham.

The line will connect with the planned Sydney Metro West that will link the city centers of Parramatta and Sydney.

The tender process has started to build almost 50 km (31 miles) of new metro railway tunnels between Greater Parramatta and the Sydney CBD on the Sydney Metro West project.

The New South Wales government has called for expressions of interest for the mega project's first two major infrastructure packages — the delivery of twin tunnels between Westmead and The Bays.

Sydney Metro West will create more than 10,000 direct new jobs and 70,000 indirect jobs, with thousands of these jobs being generated by these new tunneling contracts.

The first of four mega tunnel-boring machines are expected to be in the ground before the end of 2022.

Expressions of interest have been called for the first two tunneling contracts from Westmead to Sydney Olympic Park and from Sydney Olympic Park to The Bays. ■

Purple Line Extension TBM reaches Wilshire/Fairfax station

One of the tunnel-boring machines (TBM) working on Section 1 of the Metro Purple Line Extension Project in Los Angeles, CA reached the Wilshire/Fairfax subway station near the La Brea Tar Pits in the Miracle Mile. It is the second station that LA Metro has successfully reached via tunnel as part of Section 1.

The TBM, a 907-t (1,000-st), 122-m (400-ft) machine, named Elsie, started at the Wilshire/La Brea station in October 2019 and broke through the eastern side of the planned Wilshire/Fairfax station site about 1.6 km (1 mile) away on April 4. The TBM is now resting approximately 21 m (70 ft) below busy Wilshire Boulevard. Metro's second TBM, named Soyeon, was expected to reach Wilshire/Fairfax in about eight weeks.

Reaching this milestone is a significant accomplishment for Metro. The underground soil conditions in this area of Los Angeles represent some of the most challenging for the entire project. The agency's modern, high-tech TBMs have mined through a unique combination of soils and geologic conditions, including tar sands and methane gas.

The breakthrough also marks another milepost in the decades-long effort to extend LA Metro's subway farther west beneath Wilshire Boulevard, one of the busiest and most congested urban thoroughfares in the United States.

"This has been an enormously complex operation that Metro and its contractor, Skanska Traylor-Shea, have successfully conducted," city of Inglewood Mayor and Metro Board Chair James T. Butts said in a statement. "When this project is ultimately completed, we will have fast, frequent and reliable subway service connecting downtown L.A. and West L.A. in just 25 minutes. That will be a game changer for all of L.A. County."

Public works projects like the Purple Line Extension project are considered essential activities during the COVID-19 public health crisis. Metro and its contractors are committed to ensuring the safety of

(Continued on page 12)

Contractors chosen for Great Lakes tunnel project

Enbridge Inc. announced that it has hired companies to design and build a disputed oil pipeline tunnel beneath the channel linking Lakes Huron and Michigan, despite pending legal challenges.

The Canadian company is forging ahead with plans to begin construction work in 2021 on the Great Lakes tunnel project, which would replace twin pipes that have lain across the bottom of the Straits of Mackinac in northern Michigan since 1953.

The *Associated Press* reported that State Attorney General Dana Nessel is appealing a Michigan Court of Claims ruling last October that upheld an agreement between Enbridge and former Republican Gov. Rick Snyder's administration to drill the tunnel through bedrock beneath the straits. The case is before the state Court of Appeals, which declined to put the lower court ruling on hold while considering the matter.

Nessel, a Democrat, also has filed a separate lawsuit seeking to shut down Enbridge's existing Line 5 pipes.

But the company believes its success in court thus far creates "a path forward," spokesman Ryan Duffy said.

"We feel like it's time now for Enbridge and the state to work together and keep the project moving," he said.

Enbridge, based in Calgary, AB, Canada, planned to provide a status report to the Mackinac Straits Corridor Authority during a meeting in St. Ignace, MI. The panel was established by the law that approved the tunnel agreement.

Great Lakes Tunnel Constructors, a partnership between Jay Dee Contractors Inc. of Livonia, MI, and the U.S. affiliate of Japan-based Obayashi Corp., will build the tunnel. Arup, a multinational engineering company based in London, will design it, Enbridge said in a statement.

Line 5 each day carries 87 million L (23 million gal) of crude oil and natural gas liquids used for propane between Superior, WI, and Sarnia,

(Continued on page 16)

NEWSNEWSNEWS

Funding plan for Ottawa tunnel announced

Ontario, Canada's Premier Doug Ford, along with Caroline Mulroney, Minister of Transportation, and Kinga Surma, Associate Minister of Transportation, invited the federal government to join the province to fund at least 40 percent of the four subway projects being built in the greater Toronto area. The projects include the Scarborough Extension and the Elington Crosstown West Extension.

"Our government has a plan to build Ontario together and has joined a coalition of municipal partners to build some of the most ambitious, historic and nationally significant projects in the country," said Ford. "We have made tremendous progress in the past working with our federal partners, and we can do it again with our rapid transit plan, which includes four subways. I firmly believe these projects will not only move Ontario forward but will move the entire country forward."

The invitation to the federal government comes as the Ontario government announced the first phase of construction and tunneling work for two priority transit projects — the three-stop Scarborough Subway Extension and the Eglinton Crosstown West Extension with planned connection to Pearson International Airport, the second-largest employment zone in Canada.

Two Requests for Qualifications (RFQs) were issued, through Infrastructure Ontario (IO) and Metrolinx. They mark the first step in the procurement process to deliver on the province's commitment to build transit faster, eliminate gridlock and connect people to places and jobs.

"We are building a modern, efficient rapid transit system that provides benefits for all transit riders and taxpayers," said Mulroney. "These subway projects in Scarborough and along Eglinton will strengthen our transit network and better connect us as a world-class province, region and city."

"We've worked diligently to make great strides in building transit, creating a transit plan, establishing a historic Ontario-Toronto Transit Partnership agreement with the city and introducing legislation to build transit faster," said Kinga Surma, Associate Minister of Transportation. "Now it's time to get shovels in the ground and place orders for tunnel-boring machines to expand our subway system by more than 50 percent. Our government is moving at an unprecedented pace to deliver on the premier's transit vision for the province."

"Our government has made transit and transportation infrastructure a marquee part of our plan for Ontario," said Laurie Scott, Minister of Infrastructure. "We are moving forward with the most significant transit projects the Greater Toronto Area has experienced in generations and all of these projects will be delivered using Ontario's world-class public-private partnership (P3) model. Today marks an exciting milestone for two of the priority transit projects the three-stop Scarborough Subway Extension and the Eglinton Crosstown West Extension. It's another example that Ontario is getting shovels in the ground and we are delivering on our plan."

These RFQs outline the scope of work to design, build and finance the construction of tunnels for the three-stop Scarborough subway and Eglinton Crosstown West Extension.

(Continued on page 15)

DC Water's Potomac River Tunnel proposal approved by National Park Service

The U.S. National Park Service on April 14 approved DC Water's proposal to move forward with construction of the Potomac River Tunnel project following an environmental assessment.

The Potomac River Tunnel project — part of DC Water's Clean Rivers Project — is estimated to reduce combined sewer overflow volume into the Potomac River by 93 percent, according to a news release.

The project consists of a large-diameter deep sewer tunnel, diversion facilities, drop shafts and support structures to capture flows from existing combined sewer overflows (CSOs) along the Potomac River and convey them to the Blue Plains Advanced Wastewater Treatment Plan for treatment.

Combined sewers are designed to collect rainwater runoff, domestic sewage and industrial wastewater in the same pipe and transport it to a treatment plant. During severe weather, like heavy rainfall or snowmelt, those systems can get overwhelmed and the overflow ends up in nearby streams or rivers.

The project is needed to reduce CSOs that contribute to water quality impairment of the Potomac River and, ultimately, the Chesapeake Bay; and to comply with the 2005 Federal Consent Decree entered into by DC Water, the District of Columbia, the U.S. Environmental Protection Agency (EPA), and the U.S. Department of Justice, as amended January 2016, DC Water said in a statement.

It's not just rainwater that ends up in the overflow — there can also be untreated human and industrial waste, toxic materials and debris, according to the EPA.

The Potomac River Tunnel project aims to combat that.

In addition to reduced overflow by percentage, the project is estimated to reduce the frequency of overflows from approximately 74 to four in a year of average rainfall.

"The project includes

(Continued on page 16)

Purple Line: Phase One on pace for 2023 completion

(Continued from page 8)

all project workers during this time.

Elsie was originally lowered into the ground at Metro's Wilshire/La Brea station site in the Miracle Mile area of Wilshire in October 2018. While advancing the TBM tunneled about 19 m/d (60 ftpd). It worked five days per week, 20 hours a day. It took about five months to tunnel from Wilshire/La Brea to Wilshire/Fairfax.

Metro's TBMs are pressurized, closed-face machines that minimize ground settlement during excavation. The tunnel is lined with precast concrete segments that are bolted together to form a ring. Segments are also gasketed to make the joints between segments water- and gas-tight.

When tunneling is finished for this project section, both of Metro's TBMs will have mined nearly half a million cubic yards of earth — the equivalent of filling 2.3 million bathtubs with dirt.

"We are proving once again that we can successfully mine through some of the most challenging conditions that any subway project in the world is likely to face," said Metro chief executive officer Phillip A. Washington. "We have a world-class team that includes Skanska-Traylor Shea. The team has international tunneling experience and has proven it can also be safely done here in Los Angeles."

The project is being built in three sections. The first section between Wilshire/Western and Wilshire/La Cienega is now under construction and is scheduled for completion in 2023.

Section 2 of the Purple Line Extension Project will extend the subway to downtown Beverly Hills and Century City. Section 2 is also currently under construction and is scheduled for completion in 2025. Sections 1 and 2 are funded primarily by Measure R — the sales tax Los Angeles County voters approved in 2008 — and with a pair of federal grants.

Section 3 will then extend the project to two stations in Westwood. The passage of the Measure M sales tax ballot measure by county voters in 2016 will allow this section to be accelerated. Construction began in 2019. Metro has secured federal funds for the last section of the Purple Line Extension Project. ■

North American Tunnel Conference cancelled

The Underground Construction Association of the Society for Mining, Metallurgy & Exploration (UCA of SME) said it was disappointed to announce that the North America Tunneling (NAT) 2020 Conference, originally scheduled to be held June 7-10 in Nashville, TN, was cancelled because of the COVID-19 pandemic.

In a press release, the UCA of SME said, "It is with the safety of all involved, coupled with the uncertainty of what business and travel environments will look like in June that the difficult decision was made to cancel this biennial event.

"One of the core values of the UCA of SME is health and safety, so it is even more critical that we take measures to stay true to our principles and lead the way in these uncertain times."

"It's not the outcome we planned for, but certainly in the best interest of everyone involved," said Dave Kanagy, executive director of UCA of SME. "We appreciate the hard work and dedication that our volunteers have put in to develop another leading industry program. The UCA staff is currently looking into potential virtual options to share some of those much anticipated sessions." More information can be found online at www.natconference.com.

During NAT, the UCA of SME presents its biennial awards in Lifetime Achievement, Outstanding Individual, Outstanding Educator and Project of the Year; those winners are announced on page 55 of this issue, and the UCA is looking into alternative ways to honor these individuals. In addition, UCA is taking content from NAT online during the week of June 8. More information will emailed to UCA of SME members about this virtual learning opportunity. In addition, the NAT proceedings will be published as an eBook and available in the SME Bookstore in May.

The UCA of SME continues to make plans for future conferences for the tunneling industry including the Cutting Edge Conference Nov. 9-11 in Dallas, TX; the George A. Fox Conference in January 2021 in New York City and the Rapid Excavation & Tunneling Conference June 13-16, 2021 in Las Vegas, NV.

The COVID-19 pandemic had spread around the world, infecting more than 2.4 million people and claiming the lives of more than 165,000 people near the time of the announcement. Global travel has been restricted and numerous professional conferences have either been postponed or cancelled. The World Tunnel Congress, which was originally scheduled for May 15-31 in Malaysia, has been rescheduled to Sept. 11-17.

In Milan, Italy, Salini Impregilo and Astaldi announced that work has resumed on the M4, the new metro line for Milan. Working with the city, M4 SpA and other operators involved in the project, necessary measures have been taken to protect the health of workers as they proceed with the strategic project for the city's sustainable mobility. In order for the work to proceed, extraordinary safety measures have been adopted to protect the health of workers and avoid contagion.

About 200 workers returned to work on the $1.8 billion project.

In the United States, work on most projects has continued with additional precautions in place for worker safety. ■

TBM breaks through in Guangxi Province

In January 2020, a Robbins 5.97 m (19.6 ft)-diameter main beam TBM cleared its final hurdle when it broke through in Guangxi Province, China. The TBM excavated its first of two tunnels, an 11.9 km (7.4 mile)-long conduit for Lot 1 of the North Line Water Irrigation Project, Letan Water Reservoir, Drought-Relief. The tunnel was marked by a gauntlet of challenges, from karst cavities to fault zones and water inflows. The workers on the jobsite, contractor Guangdong No. 2 Hydropower Bureau Co., Ltd., and the owner, Construction Management Bureau for the Letan Water Reservoir, had much to celebrate after completion of what is widely regarded as the most complex and longest tunnel on the North Line project.

Boring with the Robbins Main Beam TBM and continuous conveyor system began in the summer of 2015.

"There was no precedent in this province for using a main beam TBM to excavate a tunnel longer than 10 km (6 miles). We didn't have relevant local experience to use for reference," explained Yongjiu Jin, deputy manager of the project for contractor Guangdong No. 2 Hydropower Bureau Co., Ltd. The machine did encounter a number of difficult geological obstacles as it bored through limestone rock but was still able to achieve advance rates up to 40 m/d (130 ftpd) in good ground.

Much of the geology consisted of lightly weathered limestone in rock class II to III, with some sections in class IV to V rock that required the heaviest amount of ground support, ranging from rock bolts to ring beams and mesh. "Our team encountered a coal seam, gasses in the tunnel, two large water inrushes, three fault zones up to 103 m (337 ft) long, 11 karst cavities, and more. In order to solve the

(Continued on page 18)

The Robbins Main Beam TBM bored through limestone rock and installed a full range of ground support, from rock bolts to ring beams and wire mesh.

Ottawa tunnel: Ontario government calls for RFQs for Scarborough and Eglinton projects

(Continued from page 10)

To expedite work on these projects, tunneling will begin first, to be followed by separate contracts for the balance of the work on each project.

Moving forward with tunneling on Scarborough and Eglinton West marks significant progress for the province's plan to build a world-class transportation network where new transit is built faster and at a lower cost, getting people where they want to go when they want to get there.

The Scarborough Subway Extension is a nearly 8-km (5-mile) extension of TTC's Line 2 (Bloor-Danforth), from the existing Kennedy Station northeast to McCowan Road/Sheppard Avenue, with an expected service date by 2029-30.

The Eglinton Crosstown West Extension is a 9.2-km (5.7-mile) extension of the Eglinton Crosstown LRT (future TTC Line 5) from the future Mount Dennis station to Renforth Drive, with an expected service date by 2030-31. The extension will run underground, westward from Scarlett Road to Renforth Drive. Through future phases of this project, the province is committed to establishing connectivity with Pearson International Airport.

Companies interested in bidding on these tunneling contracts must register with www.merx.com to download the respective RFQs. IO and Metrolinx will evaluate RFQ submissions and shortlist teams to be invited to respond to a request for proposals in summer 2020. ■

DC Water: Environmental approval paves the way for CSO tunnel

(Continued from page 11)

construction of diversion facilities and other supporting infrastructure to intercept (combined sewer overflows) from the existing combined sewer system and divert them to the tunnel when existing sewer system capacity is exceeded during storms. Once diverted to the tunnel, excess flows will be carried by gravity to DC Water's Blue Plains Advanced Wastewater Treatment Plant," the National Park Service said in a release.

"We have seen the Anacostia River Tunnel, with its tremendous performance, bring a resurgence to that river and its banks," said DC Water chief executive officer and general manager David L. Gadis. "We know that the projects we have planned for the Potomac will dramatically improve the health of the river and the quality of life for those who enjoy it. Cleaner rivers invite more recreation and entertainment as well as economic vitality."

The project will take place primarily on National Park Service land in northwest DC. The environmental assessment conducted by NPS found there would be no significant impact on the surrounding area.

"Clean water is vital to plants, animals, parks and people who live, work and play nearby," acting NPS National Capital Area director Lisa Mendelson-Ielmini said. "After seeing the remarkable early success of the tunnel on the Anacostia River, it's exciting for us in the National Park Service to think about the possibilities for the Potomac." ■

Great Lakes: Project still faces stiff oposition

(Continued from page 9)

Ontario. A roughly 6.4-km (4-mile) segment divides into two pipes that run beneath the Straits of Mackinac.

Environmental groups want the line decommissioned, contending the underwater pipes are aging and vulnerable to a rupture that could do catastrophic damage to the lakes and their shorelines. Enbridge says they're in good condition and sustained only minor damage from a tugboat anchor strike in 2018.

For Love of Water, an advocacy group, urged the corridor authority to halt further work on the tunnel plan. The Traverse City-based organization argued that Enbridge had failed to seek authorization for the project through the Great Lakes Submerged Lands Act as required under a common-law doctrine that holds navigable waters and soils beneath them in trust for public uses.

Bypassing those laws is "one of the most egregious attacks on citizens' rights and sovereign public trust interest in the Great Lakes in the history of the state of Michigan," said Jim Olsen, the group's president.

Duffy said Enbridge will seek construction permits from the Michigan Department of Environment, Great Lakes and Energy and the U.S. Army Corps of Engineers. ■

ITA issues call for 2020 award nominations

The International Tunnelling Association has issued a call for nominations for the 6th edition of the International Tunnelling and Underground Space Awards. The awards ceremony location and date will be announced at a later date, but it will be near the end of the calendar year.

The sixth edition of the awards will include some notable changes. This year, the ITA-AITES Awards has introduced two new categories. The first is the "Overcoming the Challenge" award for projects that dealt with either foreseen or unforeseen extreme challenges during excavation and construction. The second new category is named "Oddities of the Underground," celebrating the creativity, ingenuity and imagination of the human spirit in its endeavors underground.

The ITA 2020 Awards continue the success of the first five editions of the ITA Tunnelling and Underground Space awards in Switzerland, Singapore, France, China and in Miami, FL in 2019.

This year the entries can be submitted in seven categories:

Harvey Parker, center, was given the Lifetime Achievement award in 2019.

- Major Project of the Year — over €500 million.
- Project of the Year — between €50 million and €500 million.
- Project of the Year incl. Renovation — up to €50 million.
- Technical Innovation of the Year.
- Overcoming the Challenge.
- Oddities of the Underground.
- Young Tunneller of the Year.

Entries can be submitted through a dedicated website: https://awards.ita-aites.org/entries.

Nominations for the different categories must be related to projects for which the major civil engineering work was completed between Jan. 1, 2018 and April 1, 2020.

The Young Tunneller of the Year rewards an individual born after Jan. 1, 1986 and who has brought an outstanding contribution to tunneling. ■

Robbins: More than 29 km of tunnels will comprise North Line project

(Continued from page 14)

ground problems, there were more than 160 special technical research meetings held," said Jin.

Throughout tunneling, the contractor expressed thanks for Robbins Field Service staff. "Robbins personnel provided good technical support from equipment installation and commissioning through to tunnel completion. After the equipment was handed over to our company, they still helped us with equipment usage on our project, which makes us very satisfied with the Robbins after-sales service. Robbins really delivered: the after-sales phase was not the end of service, but the beginning of site service," said Jin.

While the completion of the first tunnel — the longest single-heading construction on record for water tunnels in Guangxi — is a milestone, there is more to do. The Robbins machine will be inspected and relaunched to bore a second tunnel 4.2 km (2.6 miles) in length. The ground conditions are predicted to be equally challenging, but the tunneling operation has some help from ground prediction methodology. Tunnel Reflection Tomography — consisting of ground prediction using seismic waves — is being used to detect changing conditions ahead of the TBM. The method can predict the distribution and scale of joints and fissures, allowing the crew to plan ahead.

Located near Laibin City, the North Line project provides much-needed drought relief using a network of tunnels totaling 29.4 km (18.3 miles). "This tunnel will realize the dream of drought control that people in Central Guangxi have had for many years. The breakthrough is the most important milestone event in this first phase of the North Line project," said Jin. ■

Coming Events

Cutting Edge Conference

2020 Cutting Edge
Nov. 9-11, 2020
Westin Galleria Hotel
Dallas, TX

UC of SME

George A. Fox Conference

George A. Fox Conference
January 23, 2021
City University New York
New York, NY

More information: Meetings Department, SME, phone 800-763-3132, 303-948-4200, fax 303-979-4361, email sme@smenet.org **www.smenet.org/full-calendar**

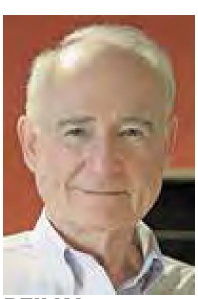
UCA of SME News

UCA presents 2020 awards

Lifetime Achievement Award to John J. Reilly, Henry A. Russell Jr. and George E. Williamson

The Lifetime Achievement Award recognizes outstanding achievements in the underground design and construction industry. These outstanding achievements have been accomplished through the design or construction of civil underground facilities, and the winners have contributed significantly to the education, planning, design, construction or rehabilitation of tunnels and underground facilities. This includes seeking advances in new methods and materials and advancing the public understanding and concurrence with the beneficial uses of underground space.

John J. Reilly, P.E., C.P.Eng., has more than 56 years of experience in the management, design and construction of large, complex infrastructure and underground projects in the United States, Australia, Canada, United Kingdom, Europe, South America and the Middle East. In 1987, he established a consulting practice in the areas of management, design, construction, contracting methods, partnering, risk management and risk-based cost estimating. He has written more than 100 papers in these areas, has chaired numerous expert panels for metro systems, tunnels, highways and bridges, and has served on several national academy panels.


REILLY

Reilly is a graduate of the University of Sydney (B.E. honors civil) and the University of California Berkeley (M.S. structures). He was president of the American Underground Construction Association from 1999 to 2001 and chair of two International Tunneling Association committees.

Henry A. Russell Jr., PE, PG, has more than 50 years of international tunnel experience. He worked for Parsons Brinckerhoff for 40 years, becoming the national program leader for tunnel rehabilitation and senior vice president. He currently works for Mott MacDonald as a principal tunnel engineer and vice president. He has written more than 40 technical papers on tunnel inspection, security, structural repairs and fireproofing. Since 1997, he has been an official delegate to the International Tunneling Association (ITA), Working Group 6-Repair and Maintenance of Tunnels, where he served as vice chair and chair. During this period, the Working Group produced three documents on tunnel refurbishment and tunnel fireproofing.


RUSSELL

Russell has been a member of the UCA Fox Committee since 2000, a member of the American Society of Civil Engineers (ASCE) Tunnel Task force since 2015 and a keynote speaker at numerous conferences. His publications include chapters on tunnel rehabilitation in the *Tunnel Engineering Handbook*, TCRP Synthesis 23, and Federal Highway Administration manuals. He is also a member of The Moles and the Transportation Research Board.

Since joining Traylor Bros., Inc. in 1985 as vice president of the Underground Division, George Williamson has procured and supervised the successful construction of dozens of tunnel contracts. He received the 1999 Golden Beaver Award for supervision, which recognizes the top tunnel engineers and managers in North America. In his time with Traylor, he led the acquisition and construction of more than 40 underground projects throughout the United States. This includes multiple award-winning projects, such as the St. Clair Tunnel, the South Bay Ocean Outfall, the Los Angeles Eastside Light Rail Transportation Project and the Queens Bored Tunnels.


WILLIAMSON

In addition to being director of special projects for Traylor's Underground Division, Williamson sits on the board of directors and the management committees that direct strategic planning for the entire company. He is a member of the American Society of Civil Engineers, The Moles and a registered professional engineer in 10 states and the District of Columbia. He is a graduate of the University of California Berkeley.

Outstanding Individual Award to Gary A. Almeraris

The Outstanding Individual Award recognizes those individuals, including contractors, engineers, owners and suppliers who have made significant contributions to the field of tunneling and underground construction and to the Underground Construction Association.

Gary Almeraris has been involved in the underground industry for more than 40 years. He is a licensed professional engineer, a blaster and an engineering graduate of the City College of New York with a masters in management from Worcester Polytechnic Institute. He is currently vice president of operations for Skanska USA Civil

ALMERARIS

Northeast and is its leading underground expert. He has worked primarily on the northeast coast and occasionally oversees large projects including transit, water supply, water power, combined sewer overflow (CSO) and highways, most of which include major underground work.

Almeraris has managed the construction of several SEM caverns, utility infested cut-and-covers, and tunnels in rock, soil and mixed face driven by conventional or tunnel-boring machines. Additionally, he has managed many varied support-of-excavation projects, including a number of frozen ground solidifications. Some of his more challenging projects have included the Big Dig, the Second Ave Subway, DC Water's CSO program and the Fulton St./WTC transit hubs.

Outstanding Educator Award to James W. Mahar

The Outstanding Educator Award is presented by the UCA Executive Committee to professors and teachers who have had an exceptional career in academia and education in the areas of underground design and construction. These individuals have also made significant contributions to the industry through their academic interests, as well as through the introduction of many student graduates into the industry. They are nominated by their peers.

James W. Mahar has more than 21 years as an educator in engineering geology and geotechnical engineering. From 1975 to 1980, he was a visiting assistant professor in the Department of Civil Engineering at the University of Illinois, Champaign-Urbana. Since 2003, he has been a senior lecturer in the departments of Civil Engineering and Geosciences at his undergraduate alma mater, Idaho State University. In his engineering geology, geologic data methods, project management and case histories courses, he focuses on design and construction of underground openings. Mahar has been a thesis adviser to 12 graduate students, and two of the dissertations have been on computer simulation of loosening loads in rock tunnels and on prediction of squeezing behavior in fault zones and soft ground tunnels. He has received three teaching/mentoring awards and the 2010 professional achievement award.

MAHAR

Mahar has more than 47 years of consulting experience in design and construction on more than 200 projects involving underground openings in soil or rock. He received his Ph.D. from the University of Illinois in geology with an engineering geology and rock/soil mechanics specialty.

Project of the Year Award to Regional Connector Transit Project, Los Angeles, CA, — a joint venture of Skanska and Traylor, WAP, Mott McDonald, Arcadis, EPC Consultants and the LACMTA

The Project of the Year Award recognizes an individual or a group that has shown insight and understanding of underground construction in a significant project, which may include a practice, developing concepts, theories or technologies to overcome unusual problems within a project.

The Regional Connector Project was unique in that it required a variety of structures and construction techniques, including TBM tunneling, deep cut-and-cover excavation, large cavern sequential excavation method and underpinning in a dense urban environment adjacent to and/or underneath numerous iconic and historic buildings. Innovative solutions were considered and implemented across the project, from semi-automatic earth pressure balance (EPB) conditioning, monitoring, tie-back removal shaft and adit, cross passage support and underpinning.

The 3-k (1.9-mile) underground light rail project extends from the Los Angeles County Metropolitan Transportation Authority's (LACMTA) Gold Line Little Tokyo/Arts District Station to the 7th Street/Metro Center Station through downtown Los Angeles. The project includes 2,880 m (9,450 ft) of 5.7-m (18 ft, 10-in.) twin-bored tunnels and three underground stations. The project connects to existing lines and stations at both ends of the new track. The entire alignment is within potentially gassy ground conditions under downtown Los Angeles.

The joint venture took over the in-progress advanced utility relocation contract as a change order at the outset of the project. A single TBM was used to bore both tunnel drives. It was rebuilt by Herrenknecht (for its third journey) and modified to navigate the extremely tight radius curves along the alignment. Traylor fabricated the precast concrete tunnel segments. Each of the twin tunnel launches was extremely challenging as the TBM mined through sandy materials with low cover 4.5 m (15 ft) underneath existing structures. Permeation grouting and compensation grouting were installed as a precaution. The owner/contractor team added a horizontal inclinometer (shape array) above each of the tunnel drives that provided settlement information 1.5 m (5 ft) above the TBM in real-

(Continued on page 57)

Women in Tunneling observe Women in Construction Week

In celebration of Women in Construction Week, UCA of SME's Women in Tunneling (WIT) group held its first tunnel tour on Feb. 15, 2020. Atkinson Construction hosted the group at its project in San Antonio, TX. The project includes the construction of three tunnel drives, one open cut and five shafts for the installation of 3,216 m (10,550 ft) of 137-cm (54-in.) welded-steel pipe.

Led by Atkinson's field engineer, Audrey Housson, and Lizan Gilbert, preconstruction executive, the tour included a full walk through the TBM tunnel, observation of pipe installation and a visit to the completed 152-m (500-ft) hand mine tunnel. In addition, the group met key project personnel and discussed possible locations and dates for future WIT tunneling tours.

WIT tunnel tour attendees included (l-r) Zuzana Skovajsova, COWI North America; Audrey Housson, Atkinson Construction; Lizan Gilbert, Atkinson Construction; Amanda Kerr, Michels Corp; Ashley Heckman, Aldea Services; Emily Haddad, Atkinson Construction and Gabrielle Ferro, Atkinson Construction.

WIT was founded in 2012 as a support association for women in tunneling to network with like-minded professionals. In 2019, WIT became an affiliate of the UCA Divison SME. The mission of the UCA Division is to promote the wise and effective development and use of underground space. Joining with UCA has enabled both organizations to expand and grow their international visibility, career opportunities and professional development.

As the number of women establishing careers in the underground design and construction industry grows, WIT focuses on providing a network and a strong support association for women to share experiences and offer mentorship in the underground industry. If you are interested in hosting or being part of a future tour with WIT, contact Emily Haddad at emily.haddad@atkn.com or Lizan Gilbert at lizan.gilbert@atkn.com for more information. Or visit the SME/UCA Community at http://tiny.cc/smecommunity-WIT. ■

UCA Young Members enhance the visibility of the underground industry

Join the UCA Young Members (UCAYM) group in support of the growth and development of young engineers and professionals in the tunneling and underground construction industry. UCA Young Members are interested in learning more about the profession, developing technical skills to use in the field, and sharing innovative technologies and research with the membership.

The group consists of people of all ages and backgrounds who believe the stability of the industry depends on the next generation of professionals. Join them for free monthly webinars and become a member of the SME community group (UCA Young Members) to keep up-to-date on university outreach, social events and discussions.

More information can be found at http://community.smenet.org/ucaym/home. ■

Project of the Year

(Continued from page 56)

time during mining. Using tight EPB PLC controls and extensive instrumentation data, the team was able to keep the settlement under 0.2 percent volume loss and remain below the contractual settlement limits.

While tunneling the first drive, the TBM encountered unexpected obstructions, two steel piles and 48 tiebacks that damaged the equipment. To recover from the delay, a third mining shift was added to the second drive. The tunnel crews set multiple records for L.A. Metro, including best single day production at 58 m (190 ft), and the project gained back two months on the schedule.

Excavating the 91-m long, 17.7-m wide, 11-m high (300-ft long, 58-ft wide, 36-ft high) track crossover cavern at a shallow depth in soft rock, beneath existing building foundations and major utilities and using the sequential excavation method was one of the most challenging parts of the project. Extensive design modeling, sensitivity analysis and daily review of field data led to the successful excavation and support of the cavern two months ahead of schedule and within the acceptable building settlements.■

Scholarships and awards available from UCA of SME

The Underground Construction Association of SME Scholarship was established to encourage undergraduate and graduate academic careers in the field of tunneling and underground construction and associated disciplines involved in the development and construction of underground infrastructure. The UCA of SME annually awards one or more scholarships to promising college students who desire to develop their skills in tunneling and underground construction.

RETC Attendance Award

The Rapid Excavation & Tunneling Conference (RETC) Attendance Award provides students with an opportunity to attend the RETC or the North American Tunneling Conference. Applicants must be full-time freshman, sophomore, junior, senior or graduate students with a designated major in an applicable field of engineering (civil, mechanical, mining, electrical, geological) or construction management. Applicants must have a demonstrated interest in the underground industry. Up to 12 recipients can be selected. Each recipient will receive:

- RETC or NAT Conference registration.
- Round-trip airfare to the conference.
- Hotel accommodations at the conference hotel.
- Conference proceedings.
- Social function tickets.
- A $200 stipend for miscellaneous cash needs.

Recipients are responsible for their own ground transportation and for other expenses, including meals, other than at social functions.

RETC Executive Committee Scholarship

RETC annually awards one or more scholarships to college students who desire to develop their skills in the tunneling industry. The total amount of the award, approximately $5,000, is apportioned to one or more students at the discretion of the RETC Executive Committee. Scholarship recipients also receive RETC attendance awards as described previously.

UCA Young Members Scholarship

UCA of SME Young Members Scholarship for NAT/RETC attendance provides selected students with an opportunity to attend conferences at which they can experience the challenges, opportunities and rewards of a career in the field of tunneling and underground construction. The goals of the award are to increase exposure to career opportunities and to provide educational and networking opportunities to future underground industry professionals.

Visit https://www.smenet.org/uca-of-sme/membership/scholarships for more information on these awards, including criteria and deadlines for application and instructions on how to apply. ■

Personal News

JUSTIN AKKERMAN (UCA/SME) has been promoted to president of Akkerman Inc., a trenchless underground construction equipment manufacturer in Brownsdale, MN. He entered the family business in 2014 as operations manager. He has been responsible for corporate administration, directing the management team, and managing the production and inventory control departments. Akkerman launched its ISO 9001:2015 quality management system and acquired several state-of-the-art machining centers resulting in production efficiencies. Previous president **MAYNARD AKKERMAN** (UCA/SME) will continue as chief executive officer and chairman of the board. ■

AKKERMAN

Brokk unveils dust supression system

To combat harmful silica dust and other airborne particles, Brokk's new Atomized Water Mist System produces an atomized fog that effectively binds dust particles in the air while also providing ground-level dust suppression.

Additionally, the mist dissipates, rather than forming puddles, for a safer, cleaner jobsite. Available for all Brokk remote-controlled demolition robots, the Atomized Water Mist System offers an ideal solution to mitigate hazardous silica dust.

Health and safety organizations have identified silica dust as a significant hazard and have enacted regulations that limit the permissible exposure for workers. Some contractors choose to use spray systems, but water droplets are much larger than silica dust. Since silica particles are more likely to bond with water droplets of similar size, Brokk engineered the dust suppression system to produce 10-micron mist droplets. This creates a fog of atomized water that captures dust particles in the air and spreads along the ground for optimal dust suppression. ■

The Atomized Water Mist System requires less water than other methods, just 0.2 L/min (6.76 oz per minute).

T&UC Tunnel Demand Forecast

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	2022	Awaiting funding
2nd Ave. Phase 2	NYC-MTA	New York	NY	Subway	16,000	20	2021	Under design
2nd Ave. Phase 3-4	NYC-MTA	New York	NY	Subway	89,600	20	2022-27	Under study
Kensico-Eastview Connection Tunnel	NYC-DEP	New York	NY	Water	10,500	27	2024	Under study
Flushing Bay CSO	NYC_DEP	New York	NY	CSO	13,200	20	2026	Under study
Bay Park Conveyance Project	NY DEC	New York	NY	CSO	18,500	8	2020	RFQ submitted
Cross Harbor Freight Tunnel	NYC Reg. Develop. Authority	New York	NY	Rail	25,000	30	2022	Under study
Metro Tunnel Program - Northern	Boston MRWA	Boston	MA	Water	23,760	10	2027	Under study
Metro Tunnel Program - Southern	Boston MRWA	Boston	MA	CSO	50,160	10	2028	Under study
Silver Line Extension	Boston Transit Authority	Boston	MA	Subway	8,400	22	2024	Under design
Narragansett Bay CSO Phase III - Pawtucket Tunnel Conveyance Tunnel	Narragansett Bay Commission	Providence	RI	CSO	 13,000 8,800	 28 10	 2020 2024	Short list Announced Under design
Amtrak B&P Tunnel	Amtrak	Baltimore	MD	Rail	40,000	32	2021	Awaiting funding
Hampton Roads Bridge-Tunnel Project	Virginia DOT	Hampton Roads	VA	Highway	7,500	42	2019	Dragados JV awarded
Alex Renew Long-Term Control Plan	City of Alexandria	Alexandria	VA	CSO	10,500	20	2019	Short list announced
Potomac River CSO Tunnel	DC Water and Sewer Authority	Washington	DC	CSO	24,000	18	2022	Under design
Superconducting Maglev Project - Northeast Corridor	TNEM/BWRR	Washington	DC	Rail	146,520	43	2021	Under design
Olentangy Relief Sewer Tunnel	City of Columbus	Columbus	OH	Sewer	58,000	14	2019	Under design
Alum Creek Relief Tunnel Phase 1 Phase 2	City of Columbus	Columbus	OH	Sewer	 30,000 21,000	 18 14	 2019 2020	 Under design 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	2021	Under design
Southerly Storage Tunnel	NEORSD	Cleveland	OH	CSO	18,350	23	2024	Under design

To have your major tunnel project added to the Tunnel Demand Forecast, or to update information on a listed project, please contact Jonathan Klug at jklug@drklug.com.

TUNNEL NAME	OWNER	LOCATION	STATE	TUNNEL USE	LENGTH (FEET)	WIDTH (FEET)	BID YEAR	STATUS
ALCOSAN CSO Ohio River Allegheny River Mononghahela River	Allegheny Co. Sanitary Authority	Pittsburgh	PA	CSO	 10,000 41,700 53,900	 14 14 14	 2022 2023 2024	 Under design Under design Under design
Enbridge Line 5 Tunnel	Enbridge	Traverse City	MI	Oil	23.760	12	2020	Contractor selected
I-70 Floyd Hill Highway Tunnel	Colorado Dept. of Transportation	Denver	CO	Highway	15,840	60 x 25	2022	Under design
W-6: Highway 90 to SW Military Drive	San Antonio Water Systems	San Antanio	TX	Sewer	28,000	10	2020	Bid date May 1, 2020
D2 Subway - 2nd Light Rail Alignment	Dallas Area Rapid Transit	Dallas	TX	Highway	3,000	22	2020	Under design
Ship Canal Water Quality Project	Seattle Public Utilities	Seattle	WA	CSO	14,250	19	2018	Lane/Salini awarded
West Seattle to Ballard Extension	Sound Transit	Seattle	WA	Transit	10,500	18	2022	Under design
LA Metro Speulvada Pass Corridor	Los Angeles MTA	Los Angeles	CA	High/Trans.	55,500	60	2020	Shortlist announced
Folsom Area Storm Water Improvement	SFPUC	San Francisco	CA	CSO	4,000	12	2022	Under design
BART Silicon Valley Phase 2 Tunnel	Santa Clara Valley Transit Authority	San Jose	CA	Subway	26,400	56	2021	Single tunnel option approved
California Waterfix 1 California Waterfix 2	Delta Conveyance Design and Const.	Sacramento	CA	Water	39,905 403,400	28 40	2020 2020	Delayed Delayed
Newell Creek Dam	City of Santa Cruz	Santa Cruz	CA	Water	1,500	14	2020	Obayashi awarded
Ashbridges Bay Outfall Tunnel	Metrolinx	City of Toronto	ON	CSO	11,500	23	2018	Southland/Astaldi JV Awarded
Yonge St. Extension	Toronto Transit	Toronto	ON	Subway	15,000	18	2016	Under study
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	2018	RFQ due April 15, 2020
Elington Crosstown West Extension	Toronto Transit Commission	Toronto	ON	Subway	40,000	18	2020	RFQ due May 29, 2020
Green Line LRT	City of Calgary	Calgary	AB	Transit	26,250	20	2018	RFQ submitted
Second Narrows Tunnel	City of Vancouver	Vancouver	BC	CSO	3,600	14	2013	Traylor/Aecon JV awarded
Annacis Island Outfall	City of Vancouver	Vancouver	BC	Water	8,000	10	2017	Pomerleau/Bessac Awarded
Millennium Line Broadway Extenstion	Metro Vancouver	Vancouver	BC	Subway	18,700	18	2020	Short list announced
Eagle Mt. Pipeline	Fortic BC Woodfibre	Vancouver	BC	Oil	29,500	13	2020	Short list announced
Northern Gateway Hoult Tunnel	Enbridge Northern	Kitimat	BC	Oil	23,000	20	2014	Under design

T&UC CLASSIFIEDS

Ad Index

Advertising Information

Hooper Jones
CENTRAL, NW U.S.
+1.847.486.1021
Cell: +1.847.903.1853
hooperhja@aol.com

Laura Lemos
EAST, SOUTH, WEST U.S.
Cell: +1.973.668.2449
Main: +1.973.822.9274
laura@boja.com

Darren Dunay
CANADA
+1.201.781.6133
Cell: +1.201.873.0891
sme@dunayassociates.com

Eberhard G. Heuser
EUROPE
+49 1520.9269629
Fax: +49 202 2838126
egh@heusermedia.com

Patrick Connolly
UNITED KINGDOM
+44 1702.477341
Fax: +44 1702.177559
patco44uk@aol.com

Gary Garvey
INTERNATIONAL SALES
+1.303.948.4243
Fax: +1.303.973.3845
garvey@smenet.org

Alaskan Way Viaduct
Replacement Program


KELLER
NORTH AMERICA'S LEADER IN GEOTECHNICAL SOLUTIONS
Bearing capacity/settlement control • Seepage control • Liquefaction mitigation • Underpinning
Excavation support • Heavy foundations • Releveling • Slope stabilization • Design-build
BENCOR
A KELLER COMPANY
HAYWARD BAKER
A KELLER COMPANY
KELLER
CANADA
CASE ATLANTIC
A KELLER COMPANY
HJ FOUNDATION
A KELLER COMPANY
MORETRENCH
A HAYWARD BAKER COMPANY
CASE FOUNDATION
A KELLER COMPANY
MCKINNEY DRILLING
A KELLER COMPANY
KELLER
North America Keller companies Bencor, Case Atlantic, Case Foundation, Hayward Baker, HJ Foundation, Keller Canada, McKinney Drilling and Moretrench have joined together and rebranded to Keller.
keller-na.com • 800-456-6548