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Job site security

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Special Editorial Supplement from the publisher of Mining engineering


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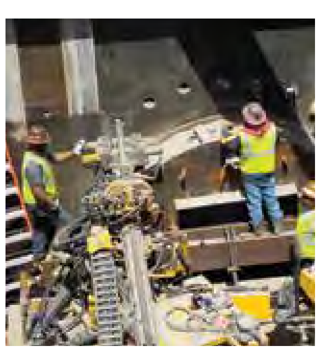

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World Tunnel Congress and ITA General Assembly updates

I've recently returned from the World Tunnel Congress (WTC), held this year in Naples, Italy. WTC is an extremely busy event. In addition to the many technical presentations, it is the only time each year where the entire General Assembly convenes. With the number of member nations now totaling 78, there is much to cover in a short period of time. I will summarize the highlights of this year's congress here.

Various elections are always a large part of the General Assembly, and this year was no different. As chair of the UCA of SME Executive Committee, I am your voting representative from the United States to the General Assembly. Prior to the elections, UCA held a breakfast for all UCA members attending the conference. The main objective of this breakfast was to inform our members of the current business before the General Assembly, including issues of governance, policy and of course, the upcoming elections. Discussions were lively, as many in the room had varying opinions on the issues and candidates. I appreciated hearing everyone's comments and concerns prior to casting votes on behalf of our organization.

To get things started, three new member nations were admitted; Kenya, Albania and Lebanon. Surprisingly, Kenya was voted in without being in attendance.

The next vote could have been dubbed "The main event" — President of the ITA Executive Council. The two nominated candidates were:

- Eric Leca, France
- Jinxiu "Jenny" Yan, China

In a very close ballot (32-30), Yan was elected, becoming the first woman to hold the position of ITA president.

The following vote was to place four new vice presidents on the Executive Council. The five nominated candidates were:

- Randy Essex, U.S.A.
- Lars Babendererde, Germany
- Arnold Dix, Australia
- Giuseppe Lunardi, Italy
- Davorin Kolic, Croatia

The first four listed above were elected. Congratulations to Randy for being elected vice president. When you see Randy at RETC, be sure to give him a pat on the back. He has been doing fantastic work with the ITA.

Because three sitting members of the Executive Council were elevated to the position of vice president, six spots on the Executive Council were open. By coincidence, six candidates were nominated.

- Abidemi Agwor, Nigeria
- Hamdi Aydin, Turkey
- Hangseok Choi, Korea
- Jeyatharan Kumarasamy, Singapore
- Andres Marulanda, Colombia
- Jamal Rostami, Iran

All six were elected.

At every General Assembly, the member nations vote for the location of the World Tunnel Congress three years out. Proposals were received from India (Goa) and Mexico (Cancun). By a wide margin, Mexico was selected as the 2022 host country.

Other business of the General Assembly centered around procedures and governance. There were numerous proposed revisions to the ITA bylaws to be voted on. Some of these were benign, others significant. Following a review of the proposed changes and considering that the agenda called for voting on all of them as a bundle, it did not seem prudent to proceed without proper assessment and discussion of the more significant proposed changes. In the hours prior to the second session of the Assembly, the

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Los Angeles' Regional Connector could face more delays thanks to labor shortages

The Los Angeles County Metropolitan Transportation Authority's Regional Connector Transit Project has faced challenges from the beginning, and it appears its completion date may be pushed back again.

The *Los Angeles Times* reported that the 3.2-km (1.9-mile) underground light rail system connecting the Metro Gold Line to the 7th Street/Metro Center Station could be delayed because of labor shortages that have slowed progress pushing the completion date to mid-March 2022, Metro said. Rail service is scheduled to begin about five months after that.

In addition, damage to the historic *Los Angeles Times* building has slowed progress. Still ahead is the intricate process of connecting the three lines in the tunnels that run between Little Tokyo and the financial district.

The estimated construction completion date has slipped about four months since December. But the contractor, a joint venture of Skanska USA and Traylor Bros., is still on track to finish before the new deadline that Metro established two years ago, officials said.

"It's probably a little bit early to be predicting what day or week they'll be finished," said project manager Gary Baker. "I'm very confident that we'll finish this as contracted."

When construction began more than four years ago, crews almost immediately encountered problems as they worked to relocate aging water pipes and fragile utility lines buried beneath streets in the heart of the central city, the *LA Times* reported.

Reinforcing and moving the lines so tunneling could safely proceed added months and millions of dollars to the project's schedule. The tunneling machine later got stuck under 2nd Street after striking a steel structure.

The project is still on track to open well before the 2023 deadline set by federal officials, who are disbursing a $670-million grant and a $130-million low-interest loan for the project.

But slower progress in recent months has eaten through some of the float in that schedule, Baker said.

The labor shortages span a wide range of jobs, he said, including management and craft labor such as concrete workers, carpenters and electricians. Without more hiring, Baker said, the project will continue to progress more slowly.

"There's a lot of strain on the construction industry in general — large businesses, small businesses, even Metro — in attracting qualified staff," Clarke told Metro's directors. "We're seeing more and more bottlenecks coming up."

Those bottlenecks could pose schedule and budget challenges as Metro prepares to build nearly a dozen new rail lines across Los Angeles in the next four decades. The historic building boom will create thousands of vacant positions in construction and engineering.

Five rail segments are under construction, including the Regional Connector, the Crenshaw Line through South L.A., and the

(Continued on page 6)

Legal battles around Seattle's SR-99 tunnel continue

The legal saga concerning the 2013 breakdown of the massive tunnel boring machine (TBM) in Seattle, WA and the subsequent two-year delay and $624 million cost overrun on lawsuit from the SR-99 project took a new twist when Thurston County Superior Court Judge Carol Murphy released a ruling that chastised contractors for failing preserve evidence in the case.

The Seattle Tunnel Partners (STP) blamed a buried steel pipe for the 2013 breakdown of the TBM named Bertha, but the contractors lost six pipe fragments and two granite boulders that the judge called important evidence in a $624-million cost-overrun lawsuit against the state of Washington.

Additionally, the project journal kept by the deputy project manager during the Dec. 4, 2013, pipe strike and its aftermath also has gone missing.

The judge called for yet-to-be determined sanctions against Seattle Tunnel Partners (STP) for losing the evidence, the *Seattle Times* reported.

"By its actions and inactions, STP consciously disregarded the importance of the missing pipe pieces and boulders in failing to preserve them," Judge Murphy said in her findings. "The loss or destruction of the missing pipe pieces and boulders is not innocent or accidental."

But Murphy also found "STP did not intentionally destroy or hide the missing pipe pieces and boulders."

Given the loss of physical evidence, the judge wrote "the importance of the missing journal is

(Continued on page 12)

Terratec to provide tunnel boring machines for Pune metro project in India

With more than 22 tunnel boring machines (TBM) delivered in India, Terratec leads all other manufacturers, combined in the country. The company announced that it will add to that lead when it delivers a number of 6.61-m (21.6-ft) diameter earth pressure balance machines (EPBMs) for the the Pune Metro Rail Project, in Maharashtra. Gulermak-Tata Projects Limited has selected Terratec to provide the EPBMs for its two underground contracts on Line 1 of the new metro.

In February, Maharashtra Metro Rail Corp. Ltd's executive director, Atul Gadgil, announced that the joint venture had won both of the twin tube tunnel packages on the north-south corridor. The 5-km (3-mile) underground section of the 16.56-km (10.3-mile) long Line 1 corridor — which runs from PCMC to Swargate — is the most challenging portion of the line, as it passes through the densely populated areas of Kasba Peth, Budhwar Peth and Mandai market.

The versatile Terratec EPBMs that will be delivered to Pune will have robust mixed-face dome-style cutterheads designed to work effectively in the compact basalt that is expected on these contracts at pressures of up to 4 bar.

As the TBMs progress, they will install 1,400-mm (55-in.) wide by 275-mm (10.8-in.) thick pre-cast concrete lining rings, which consist of five segments plus a key.

The order comes following the very strong performance of two 6.52-m (21.4-ft) diameter Terratec EPB machines that were used by Gulermak-Tata Projects JV to complete the TBM-driven tunnels on Phase 1A of the Lucknow Metro two months ahead of schedule.

"With this TBM supply order, Gulermak-Tata JV has once again reaffirmed its confidence in Terratec's TBMs, for their new projects due to the excellent performance of these machines," said Gulshan Gill, managing director of Terratec India. "In recent years, Terratec has emerged as the leading TBM supplier in the Indian market, having supplied 22 TBMs in the last five years alone. Terratec's continuing success on projects such as Phase III of the Delhi Metro Phase, Lucknow Metro, the Ahmadabad Metro and Mumbai Metro is a result of excellent tailor-made robust TBM design, prompt onsite assistance, a readily available stock of TBM spares, and highly-skilled specialised TBM support throughout the tunneling operation."

Pune is an industrial city that has witnessed much growth in the areas of corporate and industrial infrastructure over the last decade. Existing roads in the city currently carry an average of 8,000 commuters an hour in each direction. The city experiences high traffic during peak hours that leads to long hours of traffic jams along with increased pollution.

The Pune Metro aims to provide a solution to the above issues by offering a safe and eco-friendly journey with a 50-percent reduction in travel time. When complete, in 2022, Pune's Metro network will comprise three rail corridors with a total length of 54.5 km (33.8 miles). Construction of the first two phases is currently underway, while the third phase was approved for construction by the government of Maharashtra in October 2018. ■

LA Regional Connector: More challenges expected

(Continued from page 4)

extension of the Wilshire subway to West Los Angeles, which is being built in three phases.

Labor shortages typically drive up the price of bids from contractors, Clarke said, because companies end up raising salary offers to attract qualified workers. That could lead to Metro paying more to build each project.

The biggest crunch for Metro will come over the next decade, as the agency works to finish 28 transit and highway projects before the 2028 Summer Olympic Games, an initiative dubbed "28 by '28."

Twenty of the projects are slated to be finished within the decade, including the Crenshaw Line, a smaller train to Los Angeles International Airport, the Wilshire subway extension and a Van Nuys light-rail line.

Metro would need an additional $26.2 billion to build the other eight projects by then. Those include several interchange improvements, a rail line to Artesia and a Sepulveda Pass transit line.

Metro is also tracking several issues that could add costs to the Regional Connector's budget, Baker said.

That includes negotiations with the City of Los Angeles over a yard where Metro stages construction vehicles, and plans to build a permanent ventilation fan plant. City negotiators asked for $25 million for a three-year lease for the staging yard, $10 million higher than Metro had expected, Baker said.

And a new design for a pedestrian bridge from a Metro station to the Broad museum could add $6 million to the $10-million budget, Clarke said. ■

Muir Wood Lecture paper available

In 2009, the International Tunnelling and Underground Space Association created the Muir Wood Lecture in honor of Sir Alan Muir Wood.

Each year at the World Tunnel Congress a chosen lecturer gives his view on tunneling, following Sir Alan's path who had a vision of tunneling.

In 2018, Edward J. Cording, professor emeritus of civil and environmental engineering, University of Illinois at Urbana-Champaign presented the lecture, "Monitoring and controlling ground behavior at the source recent applications to pressurized tunneling."

Below is the abstract from the lecture. The full paper is available at https://about.ita-aites.org/publications/muir-wood-lecture.

Presented are investigations and guidelines for monitoring, and controlling pressurized tunnel boring machines (TBMs) to prevent ground loss, and damaging settlement to structures. The process begins in the planning stages with the owner's team and continues during construction with a coordinated program of managing, operating and monitoring the tunneling process.

Monitoring of ground movements at their source is at the heart of the observational method for geotechnical projects. In large underground rock caverns and on slopes, borehole extensometers and inclinometers have been used for over 60 years to determine the depth of zones of movements and locate the geologic features affecting stability. In urban tunneling and excavation, these instruments are used to locate the sources of ground movement that could cause damaging settlement.

For pressurized TBMs, such observations, made close to the advancing TBM, are key to understanding and controlling ground behavior.

Examples are provided of earlier, open face shield tunneling where ground behavior could often be observed directly. The process often relied on the ability of the ground to stand unsupported, and the operator was provided with equipment with which he could not always be successful.

The tunneling industry has witnessed a revolution. Pressurized face TBMs — slurry balance machines and earth pressure balance machines (EPBMs) — have enabled tunneling at greater depths under waterways and at shallower depths in urban areas without damaging settlement. Advances in recent years have included the increasing capability to coordinate and control the TBM operation and monitor key machine functions and their impact on the surrounding environment in real time as the TBM advances. Maintaining and monitoring a continuously pressurized envelope of conditioned muck and injected slurries around the face and body of the shield, and grout around the lining at the tail of the shield have resulted in improved and consistent control of ground movements throughout the tunnel drive.

In this paper, real-time records of key TBM operating parameters are coupled with real-time observations of ground movements and porewater pressures immediately around the advancing TBM. Borehole extensometers, piezometers, and directionally drilled horizontal inclinometers are used to pin-point the sources of ground movement and ground water changes around the TBM to aid in making adjustments and confirming that ground control is being achieved. The results of such observations are described for both open face shields and pressurized face TBMs on tunneling projects in Washington, D.C, Chicago, Toronto, Seattle and Los Angeles.

The benefits have been most dramatic in their application to large diameter TBMs and to TBMs driven at shallow depth in urban areas. The 17.5-m-diameter EPBM selected for the recently-completed tunneling for the Alaskan Way Viaduct Replacement project for State Route 99 in Seattle was the largest pressurized TBM to be driven beneath an urban area. To assess and mitigate risks, the owner and contractor teams built on previous experience with large diameter pressurized face TBMs, including tunnels in Porto (Portugal), Barcelona, and Madrid driven with 9- to 15-m (29- to 50-ft) diameter EPBMs. Ground improvement and reinforcement methods were implemented, but the primary and most effective ground control measures were in planning and executing the TBM operation. Continuous pressurization of the TBM face, shield steering gap and lining gap at the shield tail prevented ground loss and prevented damaging settlement throughout the drive beneath Seattle structures.

Essentially, such a tunneling operation achieves the objective described in an 1818 patent application for a tunnel shield by Marc Isambard Brunel of "opening… the ground in such a manner that no more earth shall be displaced than is to be filled by the shell or body of the tunnel" (Muir Wood, 1994, Skempton and Chrimes, 1994). For the 17.5-m (57-ft) EPBM, the settlements immediately above the shield were smallest when the tunnel was at shallow depth, and there was no surface settlement. The results were the opposite of calculations based on an assumed percentage of ground loss, which show the largest settlements and potential damage to structures occur when the tunnel is at shallow depth. That can lead to prescribing ground modification measures or adjusting the alignment to satisfy the assumption, rather than placing primary emphasis on preventing the ground loss by controlling the tunneling operation. Recent progress has made reliable prevention of ground loss possible with the real time linkage of TBM operating parameters

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Chairman's **Column:** America's Forum hosted during World Tunnel Congress

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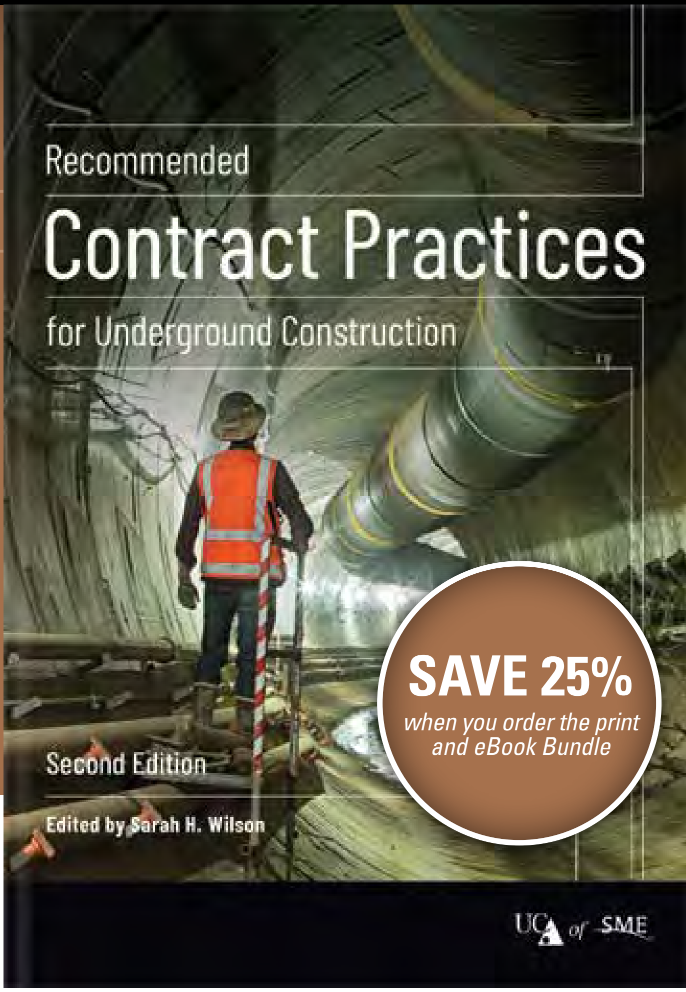
U.S. delegation successfully lobbied the ITA executive council and president to table the major revisions until such time that all member nations have sufficient time to study them and make informed decisions. Thank you, Artie Silber for running around the conference with me tracking down various executive council members.

The final vote of significance was on the so-called "Norway Proposal". Simply put, this proposal, brought forward by Norway, was a request that the ITA undergo an outside organizational assessment to ensure that the management and governance of the ITA was properly positioned to meet the needs of the growing association. This important proposal passed with overwhelming support of the member nations and Executive Council. I believe that this review can only strengthen the ITA as we move forward.

WTC 2019 was also the site of the inaugural "Americas' Forum" meeting. This forum of ITA Member Nations from North, Central and South America was first envisioned a year ago as a way for countries in the Western Hemisphere to exchange ideas and innovations in a somewhat more local environment. This initial meeting was hosted by the UCA of SME and attended by 7 of the 10 invited nations. In spite of the short time we had to meet, we were all able to agree on a vision statement and discuss mutual concerns. The second meeting of the Americas' Forum will be held in Miami during our Cutting Edge/ITA Tunneling Awards program.

Finally, this is my last column as Chair of UCA. As of July 1st, Bob Goodfellow will step into the chair position and I will become past chair (read "pasture"). It has been an honor to be your representative nationally and internationally for the past two years. I truly respect and appreciate the confidence you have placed in me and I know Bob will do an excellent job and have your full support.

Mike Roach
Chair, UCA of SME



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UCA of SME

SR-99 Tunnel: Legal woes continue in Seattle

(Continued from page 4)

heightened" because witnesses were unable to recall certain dates and communications about those items.

The pipe fragments were likely discarded into a recycling bin during an overnight job-site cleanup in January or February 2014, according to Murphy's ruling.

The steel pieces and granite boulders were being stored on a wood pallet within a 2-ha (5-acre) yard near the downtown waterfront that was closed to the public but open to a variety of tunnel workers.

The Washington State Department of Transportation (WSDOT) is mounting a vigorous defense against STP's claims that Bertha's stall was the state's fault.

The Highway 99 tunnel opened for traffic Feb. 4. The whole project cost $3.2 billion, which includes design, interchanges, street rebuilds, decommissioning of the old Battery Street Tunnel and demolition of the Alaskan Way Viaduct.

Chris Dixon, STP's project manager, said in early 2014 that the pipe became tangled in Bertha's cutting teeth, causing the machine to overheat. Grit was discovered later inside the seals of the cutter's rotary axle.

Contractors and the state argued almost immediately about whether WSDOT gave sufficient notice of the buried pipe's location. Court depositions since then indicate STP itself used the pipe to check ground water before tunneling began.

Washington state officials say the 203-mm (8-in.) diameter, 9.5-mm (0.375-in.) thick pipe couldn't have stopped what was the world's biggest tunnel drill, at more than 16 m (53 ft) across. Matt Preedy, then a deputy Highway 99 administrator, attributed Bertha's stall to "clogging in the machine," court papers say.

Insurance companies, which are also being sued, say in court papers the machine was "underdimensioned" for heavy Seattle soils, while manufacturer Hitachi Zosen, of Japan, says it operated perfectly. Despite all the sniping, the contractors refurbished Bertha to complete the tunnel.

Contractors had a duty to preserve documents and materials related to claims against WSDOT, the judge's ruling says. Among other factors, the pipe pieces were necessary for metallurgical testing and expert analysis of shear forces exerted by the cutter head against the pipe. The boulders were significant because they caused wear on the cutting teeth. ■

Muir Wood: 2018 lecture abstract

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and geotechnical observations and geotechnical observations.

It is of critical importance that there be a coordinated effort among TBM operation and geotechnical monitoring, supervision, engineering, data management, safety and construction management to assess and mitigate risks, and monitor and control the tunneling operation. Examples of such efforts are provided. Consistently controlling pressures and minimizing settlement throughout the tunnel drive serve as a demonstration to project participants and the community alike that structures along the tunnel alignment will be protected. ■

Job site security: Risk management beyond gates, guards and guns

Building and operating tunnels has been a high-stakes endeavor in terms of costs, complexity, safety and impact on contractors, owners and the public for a long time. There are many variables that need to be closely monitored and managed to construct a tunnel on-time, on-budget and safely. Once built, there are also many elements that need to be monitored and managed to operate a tunnel safely and efficiently.

Fundamentally, the risks to the safe and efficient construction and operation of a tunnel are a function of the degree of harm and the likelihood of the harm occurring. From a cyber security perspective, risk assessments used to inform decision makers and support risk responses are typically based on identification of relevant threats; internal and external vulnerabilities; the impact that may occur given the potential for threats to exploit vulnerabilities and the likelihood that harm will occur. This article focuses on creating awareness of vulnerabilities associated with technology used in tunnel construction and operation and some of the challenges associated with remediation of these vulnerabilities.

As we all know, technology has been evolving at an accelerating pace and infiltrating every aspect of our lives in new and often exciting ways. In the world of tunneling, sensors and systems that provide position and time have become accurate, rugged and cost-effective enough to come out of the research labs and into the equipment and systems used every day. There are many opportunities to employ connected computing devices and sensors to cost-effectively capture, integrate and analyze key data with minimal latency to manage risk better, improve safety and avoid surprises.

Eric Jacobs

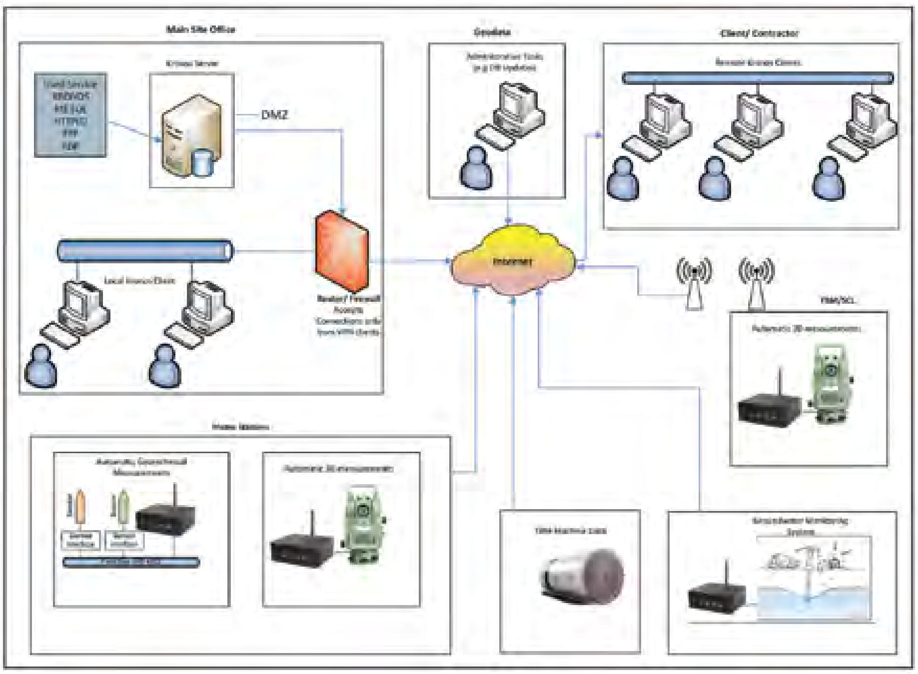
Eric Jacobs, member UCA of SME, is director at TMSAG, email ejacobs@msag.net.

A representative example where these opportunities are leveraged includes the metro project Cityringen in Copenhagen (Denmark) (Chmelina et al. 2016). This urban tunneling project will be a completely new, fully automatic, driverless metro ring line 15.5-km (9.6-mile) long and situated under downtown Copenhagen, the bridge quarters area, and Frederiksberg. The line is to have 32-km (20-mile) twin tubes bored by tunnel boring machines (TBM), 17 cut-and-cover station structures and several emergency and ventilation shafts, cross-over caverns and stub tunnels for future extensions. To manage risks, the project monitors hydro and geologic conditions; existing infrastructure such as roads, water, sewer, utilities and buildings as well as project progress data such as tunnel alignment, ring location, TBM position and operating parameters and cavern excavation rounds. A real-time monitoring system on the TBM collects data that include face pressures, grouting pressures and other operating parameters and sends this data to the contractor as well as the owner. Other parameters measured across the job include:

- Structural monitoring of stations, shafts, mined

FIG.1

Representative information technology infrastructure and network topology of a tunnel project monitoring network.



tunnels/caverns and bored tunnels including convergence measures.

- Geotechnical monitoring including surface leveling, automatic 3D surveying and in-ground instrumentation from piezometers, multi-point borehole extensometers and other sensors.
- Building monitoring.
- Ground water monitoring including dewatering, discharge and recharge water yields and volumes, levels, conductivity soundings and chemistry data.
- Environmental monitoring.
- Tunnel alignment including ring location, TBM position and cavern excavation rounds.
- Construction progress by excavated rings and face chainage.
- Ground treatment such as geometry, drilling parameters, advance rates and injection data.

For safety, a multi-parameter system measured acceleration, acoustic emissions, electric potential, temperature, humidity and air pressure to monitor the response and stability of the tunnel during and after blasting operations. Figure 1 depicts the information technology infrastructure and network topology of the monitoring network employed.

Correspondingly, the safe and reliable operation of modern tunnels incorporate a number of critical control systems distributed throughout the tunnel, typically interconnected with one or more of the owner's tunnel control centers or transportation management centers and other stakeholders (local government, law enforcement, emergency response organizations, equipment/system vendors, etc.). Typical control systems critical to tunnel safety and operations include:

- Fire protection and life safety systems.
- Fire, smoke and ventilation systems.
- Monitoring for hazardous materials.
- Kinetic energy management systems.
- Intelligent lighting control system.
- Closed-circuit television systems.
- Tunnel Communications Systems — data, voice, video.
- Radio communications systems — Highway Advisory Radio, AM/FM commercial station overrides, etc.
- Standpipe and water supply system monitoring.
- Drainage system monitoring.
- Traffic sensors — Loop Detectors, etc.
- Traffic incident detection systems.
- Environmental monitoring system — wind speed, carbon monoxide and volatile hydrocarbon information.
- Physical security.
- Over-height vehicle sensors.
- Traffic control systems.
- Variable message signs — Changeable message signs, changeable lane use signs, traffic signals, etc.
- Programmable logic controllers.

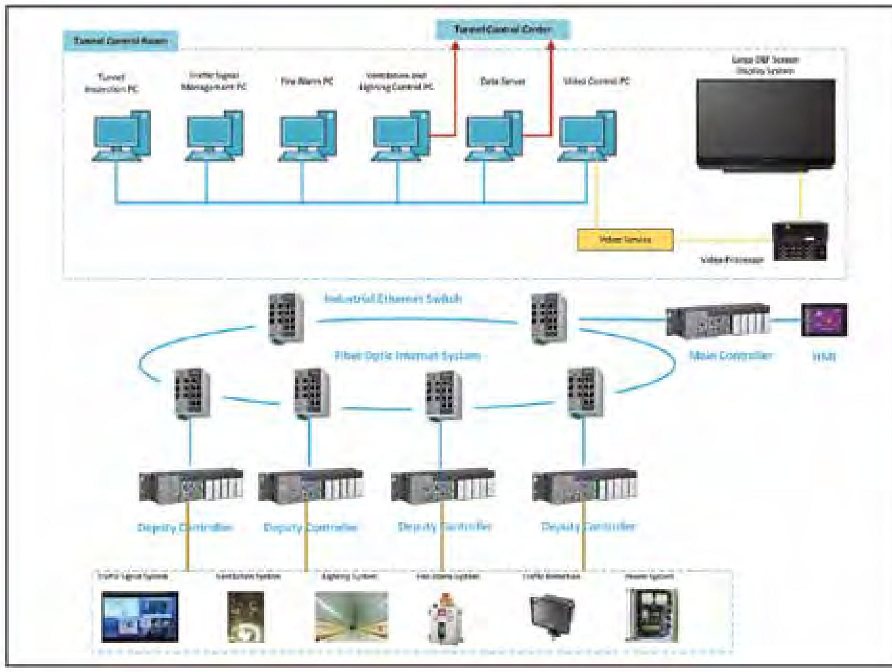
Further complicating these highly intertwined system of systems, we have the Intelligent Transportation Systems (ITS) on the visible horizon. ITS now introduces complex vehicle-to-vehicle, vehicle-to-infrastructure and even vehicle-to-anything communications.

It is easy to see the evolution of these systems. In the past, these systems were physically and electronically isolated systems running proprietary protocols using purpose-built hardware and software. Now these systems employ widely available low-cost wired and wireless devices along with industry standard computers, operating systems and network protocols. While these capabilities offer almost unthinkable advances in the safety and efficiency of tunnels, they also carry along some significant challenges when looking to deliver protection from cyber threats.

Prior to exploring examples of cyber vulnerabilities associated with these systems, it is prudent to present four additional, often overlooked, challenges faced when trying to secure these systems against cyber-attacks:

FIG.2

Representative information technology infrastructure and network topology of a tunnel control center.



- Differences in safety risk management versus cyber risk management — tunnel project monitoring and tunnel control systems lie within the intersection of cyber security and safety management. Fundamental differences between these two disciplines include that safety typically deals with random and unintentional events whose probability of occurrence can be reasonably quantified based on established techniques whereas cyber security deals with intentional, targeted attacks whose probability of occurrence is difficult to accurately quantify. Further, the level of interconnectivity of modern tunnel monitoring or control systems often overwhelms traditional hazard-analysis techniques such as failure modes and effects analysis (FMEA) and fault tree analysis (FTA). Lastly, where both safety engineers and cyber security professionals are working together to assess risk, frequent miscommunications arise as a result of a lack of familiarity with each other's discipline and terminology.
- Differences between cyber risk management approaches for IT information systems versus tunnel project monitoring/tunnel control systems — tunnel project management/tunnel control systems have many different characteristics, risks and priorities from IT information systems and different consequences in the event of compromise. The nature of the systems' devices and network connectivity makes it difficult, if not impossible to employ even basic protection approaches used in typical IT information systems such as patching and anti-virus software. Security must be implemented such that system integrity is maintained during daily operations as well as during cyber attack. Table 1 adapted from National Institute of Standards and Technology (NIST) Special Publication 800-82 Revision 2, *Guide to Industrial Control Systems (ICS) Security* offers a summary of typical differences between IT systems and tunnel project monitoring/tunnel control systems.

The impact these differences can have on operations can be seen in two representative examples where well-intentioned organizations and experienced IT system cyber professionals impacted the availability and integrity of an ICS/SCADA system causing economic impact and compromising safety. In the first incident, a vulnerability scan performed on a SCADA network caused a 3-m (10-ft) robotic arm to come out of standby mode and swing 180°. In a separate incident, a well-intentioned penetration test locked up an oil and gas company's SCADA system resulting in the inability to send gas through its pipelines to customers for four hours. (Sandia National Laboratories, 2005).

- Oversight of the design, implementation and operations of tunnel project monitoring/tunnel control systems — IT departments within contractors and owners typically employ cyber-security-savvy professionals. A paradox exists, however, that these professionals often have little to no experience with tunnel project monitoring/tunnel control system's ICS/SCADA systems and their design, configuration, maintenance or protection. Tunnel project monitoring/tunnel control systems are typically designed, installed

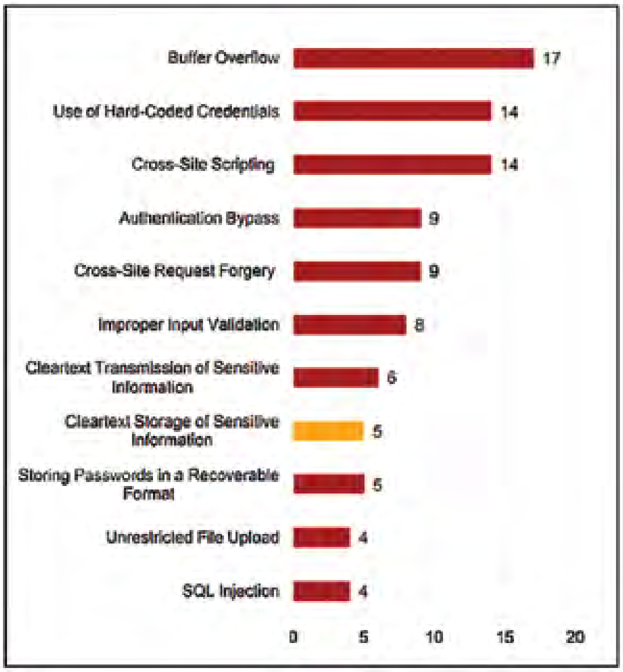
Table 1

Summary of difference between IT Systems and tunnel project monitoring/tunnel control systems.

Category	Information technology	Tunnel project monitoring/tunnel control systems
Performance requirements	• Non-real-time. • Response must be consistent. • High throughput is demanded. • High delay and jitter may be acceptable • Less critical emergency interaction • Tightly restricted access control can be implemented to the degree necessary for security.	• Real-time. • Response is time-critical. • Modest throughput is acceptable. • High delay and/or jitter is not acceptable. • Response to human and other emergency interaction is critical. • Access should be strictly controlled, but should not hamper or interfere with human-machine interaction.
Availability requirements	• Responses such as rebooting are acceptable • Availability deficiencies can often be tolerated depending on the system's operational requirements.	• Responses such as rebooting may not be acceptable because of process availability requirements. • Availability requirements may necessitate redundant systems. • Outages must be planned and scheduled days to weeks in advance • High availability requires exhaustive pre- deployment testing.
Risk management requirements	• Manage data. • Data confidentiality and integrity is paramount. • Fault tolerance is less important, momentary downtime is not a major risk. • Major risk impact is delay of business operations.	• Control physical world. • Human safety is paramount, followed by protection of the process or safe tunnel traffic flow. • Fault tolerance is essential. even momentary downtime may not be acceptable. • Major risk impacts are loss of life, harm to humans, regulatory non- compliance, environmental impacts, loss of equipment or production, social and psychological impacts on citizens.
System operations	• Systems are designed for use with typical operating systems. • Upgrades are straightforward with the availability of automated deployment tools.	• Differing and likely proprietary operating systems often without security capabilities built in. • Software changes must be carefully made usually by software vendors. because of the specialized control algorithms and perhaps modified hardware and software involved.
Resource constraints	• Systems are specified with enough resources to support the addition of third-party applications such as security solutions.	• Systems are designed to support the intended monitoring or control function and may not have enough memory and computing resources to support the addition of security capabilities.
Communications	• Standard communications protocols. • Primarily wired networks with some localized wireless capabilities. • Typical IT networking practices.	• Many proprietary and standard communication protocols. • Several types of communications media used including dedicated wire and wireless (radio and satellite). • Networks are complex and sometimes require the expertise of control engineers or engineers with specialized knowledge.
Change management	• Software changes are applied in a timely fashion in the presence of good security policy and procedures. The procedures are often automated.	• Software changes must be thoroughly tested and deployed incrementally throughout a system to ensure that the integrity of the control and monitoring system is maintained. • Outages often must be planned and scheduled days or weeks in advance. • May use operating systems that are no longer supported.
Managed support	• Allow for diversified support styles.	• Service support is typically via individual vendors for each subsystem with little if any awareness or concern for other subsystems
Component lifetime	• Lifetime on the order of 3 to 5 years.	• Lifetime on the order of 1 to 15 years.
Component location	• Components are usually local and easy to access.	• Components can be isolated, remote and require extensive physical effort to gain access to them.

FIG.3

Top 10 vulnerabilities of ICS components in 2015.



and configured by contractors with little, if any cyber security awareness and maintained by staff with little, if any cyber security awareness. Further, the common use of joint ventures, alliance partners, and outsourced services in the industrial sector has led to a more complex situation with respect to the number of organizations and groups contributing to security of the industrial automation and control system. These practices must be taken into account when developing security for these systems.

- The need for a security mindset — The fourth often overlooked challenge faced trying to secure these systems from cyberattacks is the need for a security mindset. A security mindset involves thinking about how something can be made to fail, thinking like an attacker or criminal. Thinking like this is not natural for most people, especially engineers. Engineers are typically focused on how things can be made to work and withstand unintentional and extreme events. Only recently are efforts beginning to emerge to engineer-in cyberresiliency into systems as a functional requirement.

Examples of vulnerabilities

Identification of vulnerabilities associated with tunnel project monitoring/tunnel control system infrastructure can be best obtained from open sources including Industrial Control Systems Cyber Emergency Response Team (ICS-CERT) advisories (https://ics-cert.us-cert.gov/advisories), NIST's National Vulnerability Database (NVD) (nvd.nist.gov) and SCADA Strangelove (scadastrangelove.blogspot.com). Publicly known cyber security vulnerabilities are stored in the NVD and are assigned a common vulnerabilities and exposures (CVE) identifier. CVE Identifiers are used to discuss or share information about a unique software or firmware vulnerability; provide a baseline for tool evaluation, and enable data exchange for cybersecurity automation.

The number of vulnerabilities in ICS and SCADA components keeps growing. With increased attention to ICS/SCADA security over the last few years, more and more information about vulnerabilities in these systems is becoming public. That said, due to the nature and service life of these components of tunnel project monitoring/tunnel control systems, it is likely that vulnerabilities are present in these products for years before they are revealed. In 2015, 189 vulnerabilities in ICS components were published. Of these 189, 49 percent of them are classified as critical severity and 42 percent as medium severity (Andreeva et al, 2016).

Vulnerabilities are exploitable. Exploits are readily available for 26 of the vulnerabilities published in 2015 and for many vulnerabilities (such as hard-coded credentials) an exploit code is not needed at all to obtain unauthorized access to the vulnerable system. It is also important to note that a majority of ICS security assessments show that default credentials in ICS components are often not changed and could be used to gain remote control over the system.

Based on 2015 data from the NVD and ICS-CERT, the most widespread vulnerability types for ICS components often found in tunnel project monitoring/tunnel control systems were buffer overflows (9 percent of all detected vulnerabilities), use of hard-coded credentials (7 percent) and cross-site scripting (7 percent). The top 10 most widespread types of vulnerabilities are presented in Fig. 3.

While detailed descriptions and explanations of these vulnerability types are outside the scope of this paper, a brief overview of these top 10 vulnerabilities adapted from Kapersky Lab's Industrial Control Systems Vulnerabilities Statistics are presented here:

Buffer overflow. Buffer overflow is a programming error in which software, while writing data to a buffer, overruns the buffer's boundary and overwrites adjacent memory locations. Writing outside the bounds of a block of allocated memory can corrupt data, crash the program, or cause the execution of malicious code. In total, 17 buffer overflow vulnerabilities were found in ICS components in 2015, eight of them have a high-risk level. These security flaws were discovered in different components, including SCADA systems, human-machine interface controllers, DCS and others. Four of these vulnerabilities have the highest common vulnerability scoring system (CVSS) score – 10, corresponding to the maximum impact (high-privileged access), which could have been carried out by a remote unauthenticated attacker.

Hard-coded credentials. Hard-coded credentials, such as a password or cryptographic key, typically create a significant hole that allows an attacker to bypass the authentication that has been configured by the software administrator. This vulnerability was discovered in 14 different ICS components (HMI, PLC, network devices and others), and in most cases it has a high-risk level. Almost all of the identified vulnerabilities of this type could be exploited by a remote attacker.

Cross-site scripting. Cross-site scripting enables attackers to inject client-side scripts into web pages viewed by users, which could be used to steal user authentication data (cookies), perform social engineering attacks or spread malware. Vulnerabilities of this type are present in 14 ICS components (most of them are SCADA systems).

Authentication bypass. An attacker exploiting authentication bypass vulnerabilities may be able to capture or modify privileged information, inject code, or bypass access control. Depending on the vulnerable system, such flaws can have a different nature, for example the use of a vulnerable servlet (NVD CVE-2015-6480), a web server allowing an attacker to directly access the information by ignoring the location header (NVD CVE-2015-7910), or incorrect file system architecture (NVD CVE-2015-1599). Authentication bypass vulnerabilities were found in eight different types of ICS components, including HMI, a network device, remote terminal unit and others.

Cross-site request forgery. The cross-site request forgery vulnerability exists when a web server is designed to receive a request from a client without any mechanism for verifying that it was sent intentionally. Then, it might be possible for an attacker to trick a client into making an unintentional request to the web server, which will be treated as an authentic request. This can be done via a URL, image load, XMLHttpRequest, etc. and can result in the exposure of data or unintended code execution. Four of nine vulnerabilities discovered are present in SCADA systems.

Improper input validation. Products containing the improper input validation vulnerability do not validate, or incorrectly validate, inputs that can affect the control flow or data flow of a program. Most of these flaws are related to arbitrary code execution. Eight vulnerabilities are present in HMI, SCADA system, real time operating system and OPC server components.

Clear text transmission of sensitive information. Clear text transmission of sensitive information vulnerabilities allow an unauthorized actor to sniff sensitive or security-critical data in a communication channel because the software transmits data in clear text. Communications, including login credentials are exchanged in easily readable clear text when tunnel project monitoring/tunnel control systems employ devices that do not support cryptographic protocols that provide communications security over a computer network such as Secure Sockets Layer (SSL) or these protocols are not enabled.

Clear text storage of sensitive information. When information is stored in clear text, attackers could potentially read it. Even if information is encoded in a way that is not readable by humans, techniques could determine which encoding is being used and then decode the information. This type of medium level vulnerability can be found in tunnel project monitoring/tunnel control systems' ICS components, HMI, SCADA systems, Web servers, and pumps.

Storage of passwords in a recoverable format. The storage of passwords in a recoverable format makes them subject to password reuse attacks by malicious users. Essentially, recoverable encrypted passwords provide no significant benefit over plain text passwords, since they are subject not only to reuse by malicious attackers, but also by malicious insiders. If a system administrator can recover a password directly, or use a brute force search on the available information, the administrator can use the password on other accounts. HMIs of tunnel project monitoring/tunnel control systems are the most affected by this vulnerability.

Unrestricted file upload. Unrestricted file upload vulnerabilities in software allow an attacker to upload or transfer files of dangerous types that can be automatically processed within the product's environment. These vulnerabilities have been discovered in ICS and SCADA components. For example, (NVD CVE-2015-7912), documents a high-level vulnerability where, through a servlet, it is possible to upload arbitrary Java code to a particular SCADA product and allow application properties to be imported through uploaded files that could allow arbitrary code and command execution.

SQL injection. SQL injection is the insertion of an SQL query via data input from the client to the application. Successful SQL injection exploits can read sensitive data from the database, modify database data (insert/update/delete), execute administration operations on the database (such as shut down the data base management system (DBMS)), recover the content of a given file present on the DBMS file system and in some cases issue commands to the operating system. SQL injection vulnerabilities are common and their presence has been documented in ICS and SCADA components.

Finally, no discussion on cyber vulnerabilities would be complete without discussing email phishing type vulnerabilities. Attackers use email phishing to obtain sensitive information such as account credentials; knowledge about how systems or processes work, and to install malware (software written with the intent of doing harm to data, devices or to people). The malware can exfiltrate data and provide a platform for further lateral movement within the targeted system. The latest Verizon Data Breach Report (Verizon, 2017) presents that these social attacks were utilized in 43 percent of all breaches in this year's dataset and that 66 percent of malware linked to data breaches or other incidents was installed via malicious email attachments.

Up to this point, the discussion has been around known vulnerabilities. The 2017 Verizon Data Breach Report (Verizon, 2017) once again supports the validity of this focus as, of the 1,935 breaches analyzed, 88 percent were accomplished using a familiar list of nine attack vectors. These breaches could probably have been prevented by a few simple measures. That said, tunnel project monitoring/tunnel control systems' stakeholders need to also be aware of zero-day vulnerabilities. Especially in the case of tunnel operations, the consequences of a compromise can be large enough to justify a significant, focused, organized effort in attacking this critical infrastructure. Zero-day vulnerabilities are vulnerabilities unknown to those who would be interested in remediating or mitigating the vulnerability (including the vendor of the target software). The fewer the days since day zero, the higher the chance no fix or mitigation has been developed. Even after a fix is developed, the fewer the days since day zero, the higher the probability that an attack against the afflicted device or software will be successful, because not every user of that device or software will have applied the fix. For zero-day exploits, the probability that a user has patched their bugs is of course zero, so the exploit should always succeed. Based on research conducted by the Rand Corp. (Ablon, 2017), once an exploitable vulnerability has been found, the time to develop a fully functioning exploit is relatively fast, with a median time of 22 days. Additionally, a recent Trend Micro TrendLabs research paper presents that "the average time between disclosing a bug to a SCADA vendor to releasing a patch reaches up to 150 days." Therefore, tunnel project managers and operators are faced with the fact that it is most likely that an exploit will be circulated significantly before a patch is available from the vendor. The hard-to-patch nature of many of these fielded assets further amplify this challenge.

Other approaches to gaining an understanding of vulnerabilities associated with tunnel project monitoring/tunnel control systems components include exploring Shodan and obtaining a better understanding of how adversaries operate. Shodan (https://www.shodan.io/) is a search engine for internet connected devices. As opposed to a search engine like Google that scans webpages, Shodan scans the internet for connected devices and collects data from banners, which are metadata about a software that's running on a device. Shodan collects and indexes data from connected devices that include ICS and SCADA components, IP-enabled cameras, refrigerators and traffic signals. One way of obtaining a better understanding of how adversaries operate is to explore the MITRE Corp.'s Common Attach Pattern Enumeration and Classification (CAPEC) community resource for identifying and understanding attacks located at https://capec.mitre.org. CAPEC is a comprehensive dictionary and classification taxonomy of known attacks that can be used to increase awareness of vulnerabilities within tunnel project monitoring/tunnel control systems and enhance defenses.

Remediation/mitigation strategies and best practices

The foundation for remediating or mitigating tunnel project monitoring/tunnel control systems' cyber vulnerabilities is a comprehensive and accurate identification of system components including devices, operating systems, applications and communications and how they are interconnected. Once these components are identified, known vulnerabilities associated with each component can be retrieved from open sources mentioned earlier, including ICS-CERT advisories (ics-cert.us-cert.gov), NIST's NVD (nvd.nist.gov) and SCADA Strangelove (scadastrangelove.blogspot.com) and the vendors themselves.

From that point, threat vectors that identify where an attacker may come from need to be explored. Threat vectors can include direct access, wireless, virtual private network (VPN) connections, other network connections and computers with dual NIC cards. In considering threat vectors, think like adversary and assume connectivity.

In considering priorities for protecting tunnel project monitoring/tunnel control systems infrastructure, it is helpful to consider two important concepts. The first is that knowledge of the process is essential for high-consequence disruption.

The second is that an attacker can generally have one of four effects on a compromised system component to achieve their overall objective data exfiltration, denial of service, establish a platform for lateral movement and to generate misleading information to operators or other systems/components. Application of the first concept in tunneling means to put a high priority on protecting control room and HMI components.

Application of the second concept provides for assigning a lower priority for concern about a denial-of-service attack to a sensor collecting data. Typically safety hazards associated with this scenario have already been addressed in the design of the system. Also, the exfiltration of data from sensors (with the exception of configuration information that can be used to further enumerate the target system) is typically another low priority concern whereas causing a sensor to generate valid, but misleading, information or as a platform (trusted within the target system) to access other systems/components is typically a significant concern.

Once there is a good grasp of the infrastructure's components, connectivity, known vulnerabilities and threat vectors contractors and operators can begin to see their exposure and make informed choices to methodically improve their security posture.

The fact that most cyber security breaches are based on known vulnerabilities is clearly evident in this article and is readily supported through additional research. Based on this knowledge some reasonably simple, low-cost activities can be started that would have a significant effect on the security posture of tunnel project monitoring/tunnel control systems.

- Increase and reinforce general cyber security awareness among all stakeholders and users (remember that email phishing is a significant attack vector).
- Within IT organizations, increase awareness of the unique and different characteristics of tunnel project monitoring/tunnel control systems with respect to traditional IT systems.
- Be relentless implementing and enforcing strong password policies. See new standards for password security in NIST SP 800-63 Digital Identity Guidelines (https://pages.nist.gov/800-63-3) and use two-factor authentication wherever possible.
- Be sure you know accurately your assets: How they are connected (logical and physical topologies) and how they are configured with respect to access control, protocols enabled and connectivity permissions – white-list versus black-list.
- Remediate known vulnerabilities to the extent possible, mitigate the remaining vulnerabilities including email.
- Assess cyber security impacts when any change is made to the system and periodically review and document security posture.
- Become familiar with and constantly monitor best practices guidelines and resources from organizations such as NIST (https://www.nist.gov/cyberframework) and DHS ICS-CERT (ics-cert.us-cert.gov).
- Be prepared for when an incident occurs.

From these foundational efforts, organizations should also establish a closed-loop systems approach to cyber security that includes policy, risk management, assurance (evaluating continued effectiveness, identifying new risks/vulnerabilities) and security culture (awareness). Organizations typically find NIST's cybersecurity framework core a valuable foundation. NIST's framework core consists of five concurrent and continuous functions — identify, protect, detect, respond and recover. NIST's cybersecurity framework website, https://www.nist.gov/cybersecurity-framework, offers a vast amount of useful information and tools to assist organizations. Overlaying the guidance included in NIST 800-82, *Guide to Industrial Control Systems (ICS) Security* extends the foundation for organizations focused on tunnel project monitoring/tunnel control systems.

Suggested additional specific activities under this approach include:

- Getting a free assessment from ICS-CERT.
- Downloading the free Cyber Security Evaluation Tool (CSET) from ICS-CERT. CSET is a systematic and repeatable approach to assessing security posture that includes both high-level and detailed questions related to all industrial control and IT systems.
- Minimizing the systems' attack surface.
- Establishing a process for continuous diagnostics and mitigation (www.dhs.gov/cdm)/
- Periodically, exploring emerging alternative approaches for analyzing and securing systems and used by other critical infrastructure domains, DoD and the intelligence community. Examples of these include employing data diodes to assure one-way information transfer and restricting network access and connections between allowed elements through the use of software defined perimeters.
- Consider collaborating with other tunnel operators to establish a formal or informal Information Sharing and Analysis Center (ISAC). ISACs in other sectors are trusted entities that collect, analyze and disseminate actionable threat information to their members and provide members with tools to mitigate risks and enhance resiliency.

Conclusion

Tunnel project monitoring and tunnel control systems are increasing safety and efficiency at a dramatic pace. These systems are rapidly becoming more complex and integrated with other systems and stakeholders. To economically and rapidly develop components of these systems, vendors are employing commercial off-the-shelf components and resources that include operating systems, applications, network protocols and devices. These components often carry with them cyber security vulnerabilities as awareness of the security and safety consequences of compromise is only recently being recognized.

Further, there are accelerating efforts from individuals and organizations with malicious intent to exploit vulnerabilities in these systems to achieve their objectives. Defensively, there is a gap in the availability of cybersecurity professionals with experience protecting traditional IT assets. This gap is exacerbated by the unique and distinctive nature of the ICS/SCADA components thst make up a significant part of tunnel project monitoring and tunnel control systems. Further amplifying the challenge is that most of the tunnel project monitoring and tunnel control systems are installed and maintained by operators and owners with staff distinct from these organizations' IT support staff.

While a formidable challenge, risk to tunnel project managers and operators associated with hazards created by known and unknown cyber security vulnerabilities can be considerably and cost-effectively reduced. Significant risk reduction can be realized from a few simple, low-cost, quick-to-implement actions as presented in this paper. Furthermore, there are a growing number of resources available to tunnel stakeholders to provide guidance and resources to help further reduce risk.

All that said, however, tunnels are part of the transportation systems critical infrastructure sector, one of 16 critical infrastructure sectors whose assets, systems, and networks, whether physical or virtual, are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety. It is likely they are specifically targeted by well-educated, well-funded resources with malicious intent. Defenders need to be right all the time, attackers only once. Therefore, in spite of valuable risk reduction efforts, incidents are inevitable. An incident response plan that facilitates rapid recovery is essential. ■

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Rehabilitation and expansion of the Central City Tunnel System in Minneapolis, MN

The city of Minneapolis contracted with CDM Smith to update and provide a conceptual design for improvements to mitigate surcharge flooding in the Central City Storm Water Tunnel System (CCSTS). As a part of the project, CDM Smith conducted a field survey and condition assessment of the existing tunnel system. Information from the survey was then used to update the existing XPSWMM model and develop system wide alternatives.

The CCSTS provides storm-water runoff drainage for nearly the entire area of the city's downtown commercial district. The system consists of deep storm-water tunnels constructed in the St. Peter Sandstone, approximately 21 m (70 ft) below the street's surface. The primary tunnels comprising the Central City storm water tunnel system are located below Hennepin Avenue, Nicollet Mall, Lesalle Avenue, Marquette Avenue South, 2nd Avenue South, South 5th Street, Washington Avenue South, Portland Avenue South, 2nd Street South, and Chicago Avenue South, as shown in Fig. 1. This network of tunnels conveys the runoff from a 305-acre tributary area that is generally bound by Hennepin Avenue and 1st Avenue North to the east, 12th Street to the south, 4th Avenue South and 7th Avenue South to the west, and 2nd Street South. These tunnels were constructed between 1936 and 1940, except for the Marquette Avenue South tunnel, which was constructed between 1963 and 1964.

The CCSTS operates as a gravity flow system. These tunnels were constructed within the St. Peter Sandstone layer of bedrock and emerge from the bedrock at the Mississippi River below St. Anthony Falls. The Central City and the adjacent Chicago Avenue tunnel system converge into a single outfall at the Mississippi River. The runoff discharges from the converged outfall to a side channel of the Mississippi River, called a tailrace, located near the Guthrie Theater. The Minneapolis Division of Surface Water and Sewers provided 32 historic plats detailing the plan and profile of the tunnel system.

The tunnel plans show nine different cross-section configurations. Eight configurations within the overall system generally show the same geometric "cathedral" shape with the inside dimensions varying from 1.2 to 1.8 m (4 to 6 ft) in width and 1.8 to 2.4 m (6 to 8 ft) in height. For analysis, these eight configurations were reduced to three configurations with regards to tunnel liner, cross-sectional area and support. For simplicity, the three configurations are described according to the three types of tunnel support used during construction: none required, light timber and heavy timber.

FIG.1

Central City Tunnel system.

The storm water tunnels on Hennepin Avenue, LaSalle Avenue and Marquette Avenue between 4th and 7th Street South, and Nicollet Avenue between 9th and 10th Street South all have sanitary sewers that either cross, or aligned with, the storm tunnels, but are located below the invert of the storm water tunnels. These sanitary sewers are clay pipes encased in concrete and range from 304 to 610 mm (12 to 24 in.) in diameter. The separation between the top of the sanitary tunnel and the Central City storm water tunnel is minimal, ranging from immediately beneath the storm water tunnel to 840 mm (2.75 ft).

The Central City storm water tunnel, as it approaches the convergence structure, is a 2.3-m (7.5-ft) wide by 2.4-m (7.9-ft) tall cathedral shape tunnel constructed of block below the springline, and liner above. The Chicago Avenue tunnel, as it approaches the convergence structure, is a

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2.4-m (8-ft) diameter circular brick structure. The outfall structure, below the convergence of the Central City and Chicago tunnels, has unique cross-section configurations: a mushroom shape at the convergence that transitions to a cathedral shape for approximately 15.2-m (50-ft) immediately upstream of the outfall structure at the Mississippi River.

Pressurization of the Central City storm water tunnel segments has been an ongoing issue for the city, leading to repeated and expensive maintenance repairs. The existing deep tunnel storm water system, was not designed for the characteristics of drainage inflow that consist of an increase in runoff volumes and shortened time-of-concentration caused by increasing impervious surfaces in the downtown commercial district. Pressurization of the tunnel during large, intensive rainfall events has caused the liner to crack, contributing to liner failure and erosion of the sandstone immediately outside of the tunnel liner at multiple locations. The maintenance and repair process, typically, requires identifying the void locations caused by erosion, filling the voids with grout, and repairing the cracks that led to the creation of these voids.

Geological setting

The general subsurface geological profile in the drainage system area is very consistent as shown on the available tunnel plat drawings. This general geological profile consists of:

- Overburden — sand, gravel, boulders and, in some locations, a thin layer of clay below the granular material.
- Weathered rock — described differently on profiles ranging from hardpan and boulders to broken limestone.
- Rock — predominately a 4.6 to 12.2 m (15 to 40 ft) thick stratum of limestone that serves as a cap rock to a very thin soapstone, overlying St. Peter Sandstone.

Ground water was not identified on the plat sheets. However, during recent work on the Nicollet Mall project, which is within the drainage area of this project area, CDM Smith drilled borings to a depth of 12.2 m (40 ft) without encountering any ground water.

The CCSTS is located entirely within the St. Peter Sandstone. This rock is unique in that it is composed of very uniform sand size grains that are 99 percent quartz. The rock strength is developed from compressive loads and it exhibits almost no cohesion. The sandstone becomes harder and denser with depth. The rock is also very friable. Turbulent water in contact with fresh surface of sandstone will cause a rapid disintegration of the rock.

The total unit weight of the rock as reported in existing data is 21.2 kg/m^3 ± 0.6 kg/m^3 (135 pcf ±4 pcf) . Gradation, sieve, analyses of the sandstone indicate that approximately 90 percent of the sand grains are between 140 and 60 sieve sizes (ASTM). This is indicative of a fine sand. Porosity of the rock averages 0.28. Unconfined compressive strength testing of 11 samples ranged from 4.7 MPa to 19.4 MPa (680 psi to 2,810 psi) with an average strength of 10.8 MPa (1,570 psi). Published friction angles of the St. Peter Sandstone typically range from 54° to 65°.

Hydraulic modeling

The purpose of the hydraulic modeling analysis was to determine the extent of improvements to the Washington Avenue leg of the Central City storm water tunnel in preparation for a capital improvement project that the city has scheduled for construction starting in 2020. As part of this analysis, the XPSWMM model was used to determine the equivalent hydraulic diameter needed to provide additional hydraulic capacity for the CCSTS to prevent pressurization of tunnel during a design rainfall event.

To determine whether the observed pressure surcharge in each tunnel leg was a product of downstream constraints plus tail water, or an individual tunnel leg being constrained within a segment of the tunnel, free discharge conditions were created at the points where the Hennepin Avenue, Nicollet Mall, Marquette Avenue, and 2nd Avenue tunnels discharge into the Washington Avenue tunnel. Each leg was analyzed using the 10-year, 100-year and 500-year design storms to determine the level of service of each tunnel leg discharged into the Washington Avenue tunnel. The following describes the hydraulic capacity of each of these tunnel segments when not influenced by the hydraulic grade line (HGL) of the Washington Avenue storm water tunnel:

- Hennepin Avenue: Hennepin Avenue operated without surcharge for a 10-year design rainfall, had negligible surcharge during a 100-year design rainfall and had 1.5 to 3 m (5 to 10 ft) of surcharge for a 500-year design rainfall.
- Nicollet Mall: Nicollet Avenue, including contributing flows from the LaSalle Avenue tunnel, had negligible surcharge during a 10-year design rainfall and 6 to 15 m (20 to 50 ft) of surcharge during a 100-year design rainfall.
- Marquette Avenue: The Marquette Avenue tunnel conveyed the runoff from all rain events within the crown of the pipe, including a 500-year design rainfall.
- 2nd Avenue South: The 2nd Avenue South tunnel surcharged as much as 9 m (30 ft) during a two-year design rainfall and had significantly greater surcharge during the larger design rainfall events.

The tunnel segments were recombined to assess how the hydraulic conditions of Washington Avenue, in combination with the known deficiencies in hydraulic capacity of each tunnel leg, influenced the total flow. The most significant changes occurred in the Hennepin Avenue and Marquette Avenue legs of the system, changing from

FIG.2

Proposed tunnel expansion.

no surcharge or negligible surcharge to surcharge in all design rainfall events. However, the Chicago Avenue tunnel and the converged Central City/Chicago Avenue outfalls have sufficient capacity for all modeled rainfall events. The hydraulic analysis indicates the need for hydraulic improvements to Washington Avenue, 2nd Avenue South and Nicollet Mall tunnels. The Marquette Avenue and Hennepin Avenue tunnel legs will have improved hydraulic performance after improvement of the Washington Avenue tunnel segment, and therefore does not need further analysis. The proposed 2020 construction will focus on improvements to the Washington Avenue tunnel segment.

Preliminary design alternatives

Initial increased conveyance capacity alternatives were developed for the Nicollet Avenue, 2nd Avenue South and Washington Avenue tunnel segments found to have insufficient hydraulic capacity to convey the runoff from a design rain event. The existing condition XPSWMM model was used to compute the equivalent circular cross-sectional area for each hydraulic option. Cross-sectional areas for 10-year and 100-year rainfall events were developed to establish the incremental cost differences for mitigating system pressurization risks for the respective design rain events. Based on the XPSWMM model results of these two methods the following alternatives were developed.

Expanded tunnels. This alternative increases the size of the existing tunnel cross-sectional area. The minimum cross-section area of an equivalent circular tunnel was computed for both the 10-year rainfall event (10.8 cm or 4.27 in. of rainfall in 24 hours) and the 100-year rainfall event (19 cm or 7.47 in.) of rainfall in 24 hours), as estimated by NOAA Atlas 14, Volume 8. The actual cross-sectional shape of an expanded tunnel will likely not be circular, given the characteristics of the engineering properties of the St. Peter Sandstone, available headspace between top of tunnel and top of St. Peter Sandstone, and conflicts with the Metropolitan Council Environmental Services (MCES) interceptor. An in-depth description of the shapes and cross-sectional areas considered is presented in the construction alternative section.

Parallel tunnels. This alternative involves construction of a new parallel tunnel adjacent to the existing tunnel. The minimum cross-sectional area of a circular parallel tunnel was computed for both the 10-year design rain event and the 100-year design rain event. A parallel tunnel could either be circular or it could be another shape if any of the constraints described in the Tunnel Expansion option are encountered. Tunnel sizes for the 10-year and the 100-year rainfall events are discussed in the construction consideration section of this paper.

Final alternative. After the initial alternatives were developed for the entire system, additional refinements were made to the model to specifically address the proposed 2020 project along the Washington Avenue Tunnel alignment. For this section, a combined approach was proposed that would construct a new parallel tunnel east and west of Portland Avenue and expand portions of the existing tunnel alignment along Portland Avenue and at the junction with the Chicago Avenue tunnel system.

Geo-structural analyses

Concurrent with the hydraulic analysis, CDM Smith completed a geo-structural evaluation of the existing tunnel system with the goal of identifying and evaluating any risks associated with enlarging tunnel cross-sections to increase hydraulic capacity of the system and for repairing the existing tunnel segments.

Existing tunnel analyses. To analyze the existing tunnel system, Rocscience Phase 2 software program was utilized. After review of the existing tunnel plats, five existing tunnel configurations were identified for evaluation. The existing tunnel materials were modeled using Mohr-Coulomb failure criteria to account for the lack of reinforcing steel and an inability to resist tensile stress. Therefore, the model assumed that when a very low tensile stress was applied to the liner failure of the tunnel liner would occur. The analysis configurations consisted of the following:

- Profile analysis of the excavation of the storm water drainage tunnel at locations where it crosses directly above an existing sanitary sewer tunnel. This analysis was performed to evaluate the magnitude of change in stress on the existing underlying sewer tunnel due to excavation above it.

- **Cross-sectional analysis.** An analysis of different support types was performed using adjusted rock strength values depending on the existing liner support system, including no timber, light timber and heavy timber support behind the liner. The analysis consisted of applying a cyclical internal pressure to the tunnel representing loads experienced during a 100-year rainfall event, as predicted by the XPSWMM existing conditions model, developed by CDM Smith. The frequency of the cyclical loading was based on a review of five years of historic pressure data provided by the city. During this five-year period, there were six events that surcharged the tunnel at the pressure meters. These surcharges ranged from 1.2 to 11.6 m (4 to 38 ft) above the tunnel crown. For the modeling, we extrapolated this to 20 surcharge loadings, representing the occurrence of one surcharge event every five years for a period of 100 years. The applied internal pressure represented by the 100-year rain-event is predicted to be 35 psi, (0.24 MPa) or 24.6 m (80.7 ft) of water. This represents a factor of slightly greater than twice the measured event. Each of the three different existing liner conditions and locations, were modeled as follows:
- **No lining support.** There are several locations shown on the city's tunnel plats where the tunnel liner is shown as concrete placed against the sandstone without initial support. Figure 3 represents a typical No Support segment. The average rock strength parameters were used, without strength reduction, since there is no initial liner support. It was assumed that the St. Peter Sandstone at these locations was in good condition, with few joints or loose materials and a strength reduction was not applied to the model.
- **Light timber support.** At locations where light timber support was identified, the drainage tunnel is approximately 1.6-m (6-ft) high by 1.6-m (6-ft) wide. A light wood support encompasses the upper portion of the tunnel from springline to crown and back to the springline in a trapezoidal configuration. It was assumed that the ribs were used in locations where the rock quality exhibited some joints or fractures, requiring some additional initial support. To account for this condition, the model used a reduced rock strength of the intact rock. It is assumed that the timber supports provides a seepage path for ground water outside the tunnel and leakage through the tunnel to cause erosion of the sandstone. This results in a source of sand to migrate through cracks in the lining and creates an ongoing process of deterioration

FIG.3

No lining support.

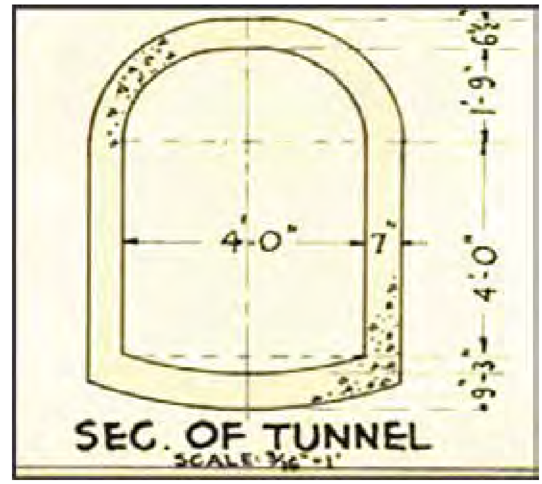


FIG.4

Light timber support.

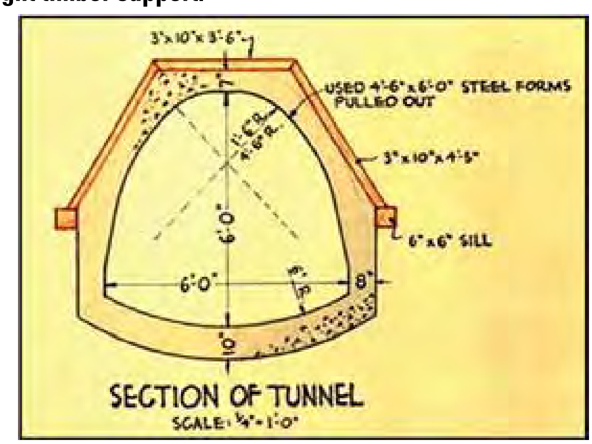
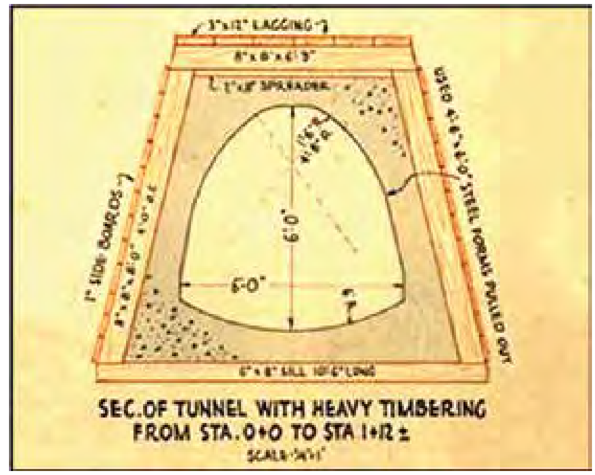


FIG.5

Heavy timber support.



of lining support by creating progressively larger areas of unsupported lining.

- **Heavy timber support.** Heavy timber support locations consist of wood ribs that fully surround the tunnel perimeter with wood lagging. Heavy timber supports were used where the rock quality was significantly poorer than at other segments of the tunnel, requiring this stronger initial support. To account for this condition, the model used the reduced rock strength of the intact rock. The same process of loss of strength of the initial support system was used to model the behavior of the tunnel as a function of time and cyclical loads.
- **Reduction in liner strength.** The purpose of a reduction in strength model was to account for degradation of the underlying timber supporting the tunnel liner related to the environmental cycles of wet and dry conditions. As the wood shrinks in volume and decreases in strength, deformation of the sandstone would follow with each cyclical loading due to a storm event. This loss of external support originally provided by the sandstone, causes a tensile loading on the unreinforced segments of the concrete liner. The tensile loading results in liner cracks. This creates a pathway for seepage of ground water from outside the tunnel liner during non-storm events, and leakage into the sandstone during a pressurized storm event to cause erosion of the sandstone. The resulting sand migration through liner cracks likely results in an ongoing process of cracking of liner by creating increasing areas of unsupported lining over time. To account for this long-term reduction in liner strength, it was assumed that the timber strength reduced by 5 percent between each cyclical loading event.
- **Concrete liner loading.** This model provided an assessment of the liner after each loading event was conducted. Providing there was continuous rock support against the liner, deformations were found to be minimal. However, where joints were formed due to shrinkage of the unreinforced concrete, the measured cracks were of sufficient size to allow passage of sand grains into the tunnel. This loss of ground was modeled by assuming a void behind the tunnel lining at each tunnel crack.
- **Combined effects.** To evaluate the locations where several factors may increase the loads, an analysis was performed taking into account a combined effect of nearby sanitary sewers, the weakened condition of the tunnel lining, and disturbance to the rock.

Expansion of the tunnel system

In addition to performing an analysis of the existing tunnel, CDM Smith performed a similar analysis on the proposed parallel and expanded tunnel configurations. During the analysis, two constraints were identified for the proposed tunnel expansion.

A review of the relationship between the existing tunnel and the caprock above the tunnel, as drawn on the tunnel plats, showed that several tunnel segments are close to the caprock and have limited space available for vertical tunnel expansion without penetrating the caprock. According to the historical data, tunnels excavations, at elevations above the limestone caprock, are significantly more challenging to support and are double to triple the construction cost than if the excavations were below the caprock. Therefore, primarily horizontal tunnel expansion, with limited vertical expansion, was evaluated. To maintain a gravity system, lowering the invert for expansion was eliminated from consideration.

Additionally, there are several adjacent sanitary and storm drain tunnels that either share a wall or are very close to one another. Because of these adjacent tunnels, it was concluded that the storm tunnel cannot be lowered, or substantially re-aligned due to the conflicts created by these nearby, and crossing, sanitary tunnels. Therefore, the adjacent tunnel expansion analysis only evaluated the option to increase the cross-sectional area of selected tunnels along their existing alignment to increase the hydraulic capacity of the storm water tunnel system.

For expansion of the existing tunnel two possible configurations were identified and evaluated. The configurations consisted of the following:

- **Excavation within the existing tunnel.** The increase in the tunnel cross-section would be constructed using sequential excavation method to reduce excessive stresses on the lining left in place. CDM Smith assumed a sequential excavation on both sides of the existing tunnel would require a minimum width of 2.4 m (8 ft) for equipment access. The excavation width would likely result in a flat roof that would not be stable as a function of the sandstone structure. However, the sandstone could be made stable with rock bolts fully anchored into the overlying limestone rock.
- **Excavation adjacent to the existing tunnel.** To evaluate this condition, sequential excavation of tunnel adjacent to the existing tunnel to a width of 2.4 m (8 ft) was assumed. Additionally, assuming a relatively flat excavation roof this excavation can be made stable with rock bolts anchored into the limestone.

Results

System rehabilitation. The Phase 2 model results indicate that the existing tunnel structures are stable where the tunnel liner is in contact with the St. Peter Sandstone. However, accumulations of sand can be an indication of eroded sandstone behind the liner, causing additional stress on the liner. It is assumed that the reason for these deposits is the combination of deterioration of the wood supports and the natural behavior of the friable sandstone that causes the fine sand to erode as the ground water moves along the outside of the tunnel liner. The basis for this assumption is that the tunnel liner consists of unreinforced concrete that ranges in thickness from 178 to 350 mm (7 to 12 in.), based on the details shown on the tunnel plats provided by the city. There is no indication of expansion joints being installed in any of the tunnels. Inspections of the tunnels indicated that spacing of vertical cracks and transverse cracks averaged about 17.4 m (57 ft) apart, measured along the tunnel axis. Considering that 90 percent of the sandstone grain size is fine sand and can pass through about 90 percent of the observed cracks, the possibility of sand grains migrating and, thus, creating void spaces, as shown in the analyses, self-perpetuates the deterioration of the tunnel lining as a function of surcharge loading. Based on the Phase 2 analysis, an increase in cracking frequency and crack width should be anticipated in locations where poor rock conditions or timber supports are present. This is supported by the locations where cracking was observed in the inspection data.

Some rehabilitation of the existing tunnel system is required in the form of repairing the cracks and filling any voids that are present behind the lining to stop further long-term deterioration of the liner. Determination of the locations and approximate volume of voids behind the liner could be conducted by an extensive geophysical survey from inside the tunnels. The results of such a survey would then be used to develop a program for repairs to the tunnel. This rehabilitation operation would mitigate the risk of failure for the existing tunnel system. However, it would not provide any increase in the hydraulic capacity of the tunnel. Therefore, the tunnel would still be subject to surcharge and street flooding.

System expansion. The modeling performed indicates that, where there is adequate sandstone cover, the tunnel can be enlarged laterally requiring minimal vertical expansion to create a stable shape. To maintain stability of the existing tunnel, which must remain in use during construction, external braces to support the tunnel liner would be required. Rock anchors and a new shotcrete liner would be required for tunnel support. Depending on the increased size of the tunnel, excavation can be performed either by a hydraulic lance or a roadheader. These excavation procedures will be discussed in greater detail later.

As the tunnels advance closer to the river and maintain their gravity slope, the sandstone thickness above the tunnel crown increases and there is adequate sandstone cover to expand the tunnel upward and maintain a cathedral shape for stability purposes. This expansion should be limited in height to maintain about 0.7 m (2 ft) of sandstone above the crown of the expanded tunnel cross-section. A first estimate of the cathedral shape can be calculated based on the friction angle of the sandstone. The height above the springline of the tunnel is about the sum of half the existing tunnel width plus the proposed increase in the width divided by tangent of the friction angle divided by two.

$$\text{Height above springline} = \frac{\frac{W}{2} + \Delta W}{\tan\left(\frac{\phi}{2}\right)}$$

The advantage of a vertical expansion in the sandstone is that it eliminates the need for the rock anchors.

There are relatively short segments of the existing tunnels that are shown to have heavy timber support. Our interpretation of using this initial support system is that the rock is in poor condition relative to the other sandstone encountered in the CCSTS. These areas may require some additional ground modification such as grouting or using a welded wire mesh to prevent fall out of rock during the excavation for the tunnel expansion.

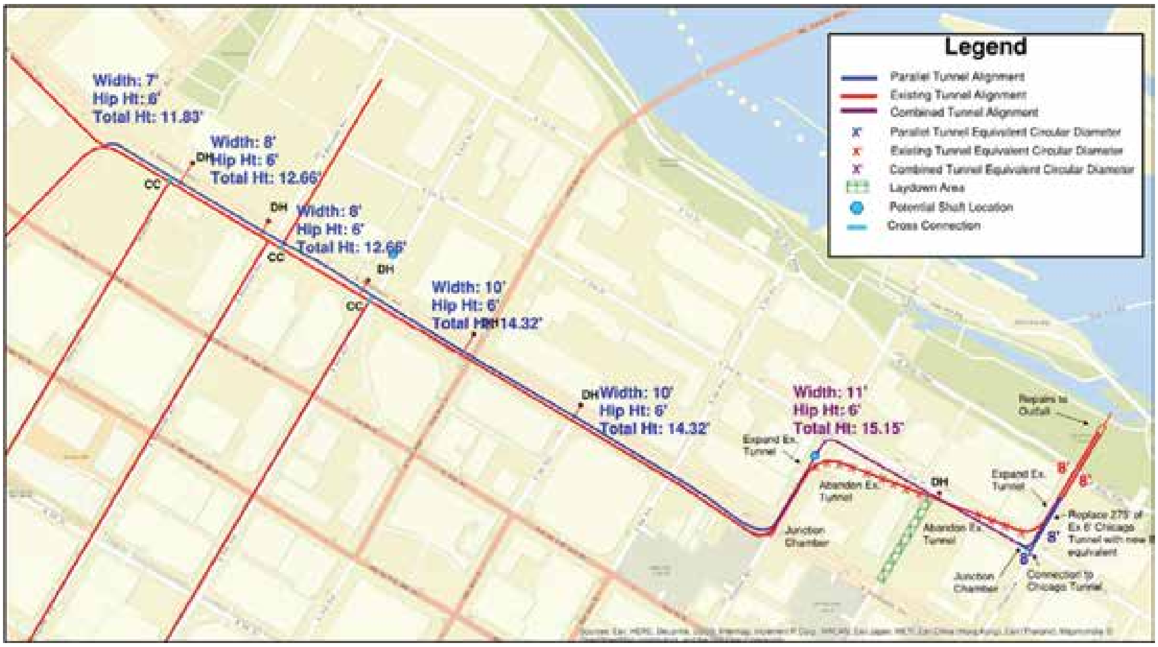
Proposed tunnel construction

As previously stated, construction of the Washington Avenue portion of this project is anticipated to begin in 2020. The preliminary alignment consists of both a parallel tunnel and some portions of the alignment where the existing tunnel will be expanded to meet the hydraulic capacity requirements. The required hydraulic capacity of the parallel tunnels would range in size from the equivalent of a 2- to 3.6-m (6.5- to 12-ft) internal diameter circular tunnel. The changes in the proposed size of the parallel tunnel, need to maintain flow in the existing tunnel and location of several cross passages greatly increase the complexity of the proposed construction. The following tunneling methods were considered for construction of a parallel tunnel:

- Hydraulic lance. The original tunnel construction used hand-held lances that emit highly pressurized streams of water that cut through the sandstone. The benefits of the approach are the ability to excavate in small spaces and to create noncircular shapes. The disadvantages include slower pace of excavation and limited number of contractors having experience with the hydraulic lance. Hydraulic lances are advantageous as a secondary method used for areas, such as transition structures, that will have a unique shape that cannot be created by a boring machine.
- Tunnel boring machine (TBM). Advantages include large boring face and efficient boring speed. Disadvantages include need for large -diameter access shaft, longer time to set up and inability to maneuver machine through tight radius curves.
- Road header machine. Advantages include smaller area needed for equipment installation, and ability to maneuver into non-circular shapes and non straight alignments. Disadvantages include slow rate of advancement and the need for more

FIG.6

Proposed tunnel construction.



personnel in the tunnel.

The hydraulic lance method has not been used for several years in the Minneapolis area and finding labor and equipment using this method can be a limitation for this method. Generally, a TBM is a more economical method of tunnel excavation given the proposed length of approximately 1,066 m (3,500 ft). However, the alignment requires three 90° turns where new shafts would be required. The tunnel alignment also would be required to cross six lateral connection tunnels. An additional limitation for excavating the tunnel with a TBM is that the tunnel diameter is set by the machine. The required hydraulic capacity reduces to the west and therefore a TBM would perform unnecessary excavation.

The use of a roadheader also has limitations. These limitations are based on the size of the machine versus the excavation size. Roadheader power and ability to cut rock is a function of the machine size. To excavate a tunnel that is only about 2.4 m (8 ft) in height and of the rock strength presented in the modeling report a small machine will be sufficient. A hydraulic roadheader is able to excavate the rock into any cross-sectional shape that has been determined to be the most stable, creating tunnels that are able to obtain the required equivalent hydraulic capacity as it changes along the alignment. The other advantages are: it can make very short radius turns that would eliminate the need for a shaft extending to the street.

Use of the road header also allows for construction of a non circular tunnel and is particularly apt for constructing a tunnel with a non circular (cathedral or other) shape that takes advantage of the properties of the St. Peter Sandstone. The disadvantages to the roadheader are that the shape is not circular. Because of the high quartz content tool wear can be expected to lead to higher tool wear/replacement and advancement rate is less than that of a TBM.

Conclusion

Final design, construction and rehabilitation of the Central City Tunnel system will face many challenges: Contractor will be required to maintain the existing flow in the tunnel; Project is located within a densely populated urban setting with a myriad of shallow utilities, heavy-volume traffic streets making it difficult to locate shafts and staging areas; Unique engineering properties of the St. Peter Sandstone present their own challenges where the ground behavior can be unpredictable during construction. However, the expanded tunnel system will greatly improve the performance of the tunnel system; reduce surface flooding and annual maintenance cost. ■

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Final design of the River Des Peres tunnel in St. Louis, MO

The Lower and Middle River Des Peres (LMRDP) CSO Storage Tunnel is the largest single component of Metropolitan St. Louis Sewer District's (MSD) CSO control system improvements planned to meet consent decree requirements for MSD's Lemay Service Area. The 13.7-km (8.5-mile) long, deep, hard rock tunnel will have a finished diameter of 9.1 m (30 ft). Beginning at the Lemay Wastewater Treatment Plant (WWTP), the alignment follows the channelized River Des Peres to the outfall of the existing Forest Park tubes, as indicated in Fig. 1.

The project includes three construction shafts, 34 intakes and a deep, cavern-style pump station located adjacent to the WWTP. The tunnel will be driven from the Defense Mapping shaft to the Macklind shaft. Another shaft is located near the midpoint at the tunnel in River Des Peres Park.

The Forest Park intake, located at the upstream end of the tunnel just beyond the Macklind shaft, is a large, tangential vortex intake structure. With a peak flow rate of 170 m^3/s (6,000 cfs), it will have a 6.1-m (20-ft) diameter dropshaft to transfer flow into the tunnel.

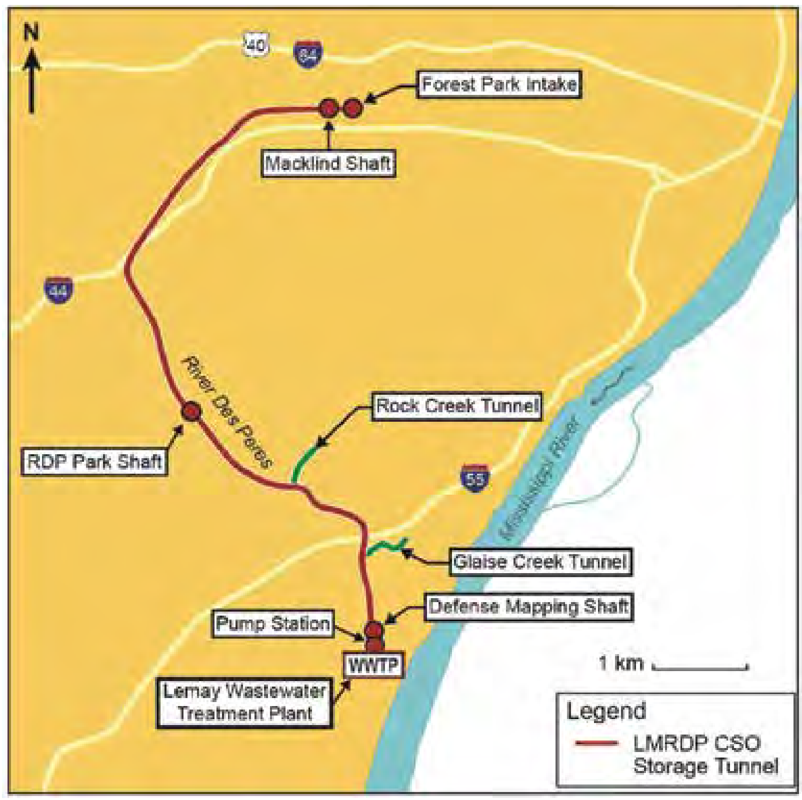
The project includes another three large tangential vortex-flow intake structures with peak flow rates ranging from 28 to 44.5 m^3/s (990 to 1,570 cfs). These large intakes are located at points where three large sewers (formerly creeks) enter the River Des Peres. Dropshaft diameters for these intakes range from 3 to 3.7 m (10 to 12 ft) in diameter. The 30 remaining intakes are smaller tangential vortex-style, with dropshafts in the range of 0.8 to 1.7 m (30 to 66 in.) in diameter.

Each intake structure drops flow into a deaeration chamber constructed adjacent to the tunnel at tunnel depth. Intake tunnels transfer flow from the deaeration chambers to the main tunnel. Most of the intake tunnels are short. However, two are long. The Glaise Creek tunnel will extend 762 m (2,500 ft) from the main tunnel to the Alaska Park intake, while the Rock Creek tunnel will extend 823 m (2,700 ft) from the main tunnel to the Rock Creek intake.

The dewatering pump station, located at the downstream end of the tunnel, will be built inside a large, horseshoe-shaped cavern with two access shafts. Excavation of the cavern and its access shafts will be performed by the tunnel contractor. Build-out of the dewatering pump station will be performed under separate contract.

FIG. 1

Project alingment.



Geologic conditions

St. Louis lies at the northeastern tip of the Ozark Uplift and is bordered to the east by the Mississippi River and the north by the Missouri River. Physiographic regions in the St. Louis area include alluvial plains along the rivers, hilly uplands located in the southern portion of St. Louis County,

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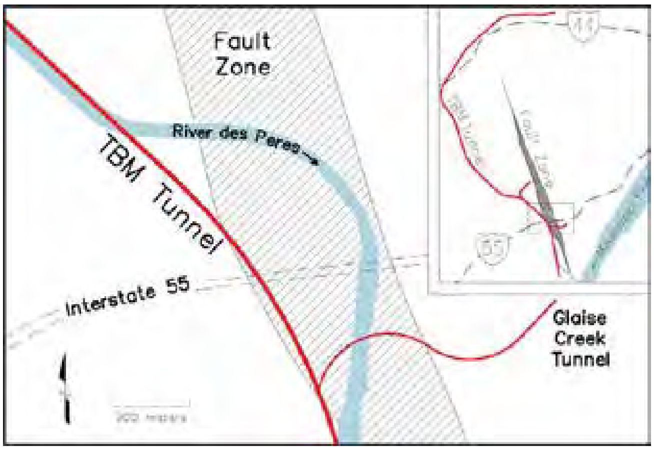
FIG.2

Location of the fault zone.



and the rolling upland located in the central and northern portions of the county. The uplands are characterized by a relatively thin veneer of silty and clayey soils overlying bedrock.

Bedrock in the region is comprised of horizontally stratified limestone with some dolomite and a few thin shale layers. The rock is generally intact but at tunnel depth can be slabby in the crown, where it breaks along bedding planes. The stratified nature of the rock will inhibit the downward movement of ground water, except along faults. Some of the limestone layers are very strong, with unconfined compressive strength (UCS) in excess of 200 MPa (30 ksi).

A large fault system crosses the tunnel alignment, as shown on Fig. 2. This fault zone contains a number of high-angle faults with both normal and reverse movement and up to 12 m (40 ft) of vertical offset. Some of the faults contain several feet of gouge, along with zones of highly fractured rock and rotated blocks. Deep weathering and hydrothermal mineralization are present in some areas.

Shafts

Each of the three construction shafts are designed for an internal diameter of 13.7 m (45 ft).

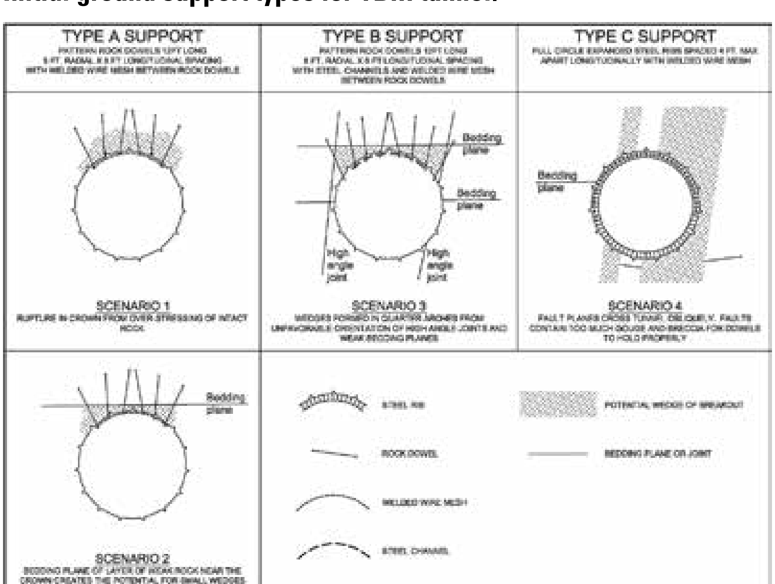
At the Defense Mapping site, the 22-m (73-ft) thick soil zone consists of fill overlying alluvium. The alluvium is potentially contaminated due to prior usage of the site. Concrete diaphragm walls are required for support of excavation, in order to restrict the flow of potentially contaminated ground water, in compliance with restrictions imposed by an environmental covenant. Additionally, pre-excavation grouting of the upper section of bedrock is required prior to concrete diaphragm wall construction. This approach was determined to be the best method for limiting the movement of contaminated ground water into the shaft.

At the River Des Peres Park shaft, the 7.3-m (24-ft) thick soil zone consists of fill overlying alluvium, which is required to be pre-supported with sheet piles. At the Macklind shaft, the 11-m (36-ft) thick soil zone consists of fill and weathered shale, which can be supported concurrently with excavation using liner plates or ring beams with timber lagging.

At each shaft, the underlying rock will be supported with rock dowels, welded wire mesh and shotcrete.

FIG.3

Initial ground support types for TBM tunnel.



Tunnel boring machine (TBM) tunnel

The tunnel boring machine (TBM) tunnel will be excavated with a single TBM beginning at the Defense Mapping shaft and terminating at the Macklind shaft. Near its mid-point, the River Des Peres Park shaft can be used for major TBM maintenance, if needed.

All muck from the TBM tunnel will be removed through the launch shaft. The first 230,000 m^3 (300,000 cu yd) of muck will be used to fill the site for future construction of the dewatering pump station and enhanced high rate treatment facility. Prior to construction of the LMRDP Tunnel, the general area around the shaft and the dewatering pump station will be raised above current grade with processed shot rock and tunnel muck from the adjacent Jefferson Barracks Tunnel. Construction of the Jefferson Barracks Tunnel began in March 2017.

The rock in the tunnel has been grouped into three types according to expected behavior related to support needs and potential difficulty of advancing the excavation due to stability issues.

- Type A ground needs light-to-minimal

support with the focus on controlling overstress failure in the crown area and isolated wedges. Type A ground typically correlates to Rock mass rating (RMR) values greater than 60.

- Type B ground needs substantial support but can hold pattern rock dowels. The ground tends to be blocky such that progressive raveling can occur, if the ground is inadequately supported. Thinly bedded strata under high horizontal stress conditions can produce Type B ground. Another cause of Type B ground is the presence of multiple intersecting joint sets. Type B ground typically correlates to RMR values between 60 and 40.
- Type C ground does not hold rock dowels well because of gouge, weathered seams, voids or tendency of the rock to deteriorate.

Figure 3 shows the initial support requirements for each of the three ground types in the TBM tunnel. Based on analysis, 80 percent of the tunnel is expected to require Type A support, while 18 percent will require Type B support, and 2 percent will require Type C support.

The large fault system crosses the TBM tunnel in the vicinity of Interstate 55, as indicated in Fig. 2. The tunnel has been routed around the worst part of this area, but still runs along the edge of it. Probing and pre-excavation grouting will be used during excavation to reduce the potential for ground and ground water inflow problems in the I-55 fault zone.

Ground water inflow into the excavated tunnel is expected to be around 900 Lpm (500 gpm), assuming the pre-excavation grouting program in the fault zone is properly completed.

Pump station cavern

The pump station cavern consists of a 9.1-m (30-ft) diameter north access shaft, a 15-m (50-ft) diameter south access shaft and a 46 m (150 ft) long by 18 m (58 ft) wide by 26 m (84 ft) high cavern, as illustrated in Fig. 4. The cavern and access shafts are located adjacent to the Defense Mapping shaft.

Because of the environmental covenant, the soil zone at the north and south access shafts will require concrete diaphragm walls for initial support. Support of the underlying rock will be through the use of rock dowels, welded wire mesh and shotcrete.

At cavern depth, ground conditions consist of alternating limestone and dolomite layers with occasional thin shale layers. A thinly bedded, relatively weak limestone layer, several feet thick, is present about 3 m (10 ft) above the crown of the tunnel.

The cavern will be excavated by drilling and blasting a top heading from the shafts toward the center of the cavern. The remainder of the cavern and shafts will be excavated in benches to bottom. Initial ground support in the cavern crown consists of 5.8-m (19-ft) long, high-capacity, tensioned rock bolts at 1.5 m (5 ft) spacing and split-spaced 3.7-m (12-ft) long rock bolts around the center section of the cavern crown and welded wire mesh (Fig. 5). High-capacity, 5.5-m (18-ft) long, grouted rock dowels and welded wire mesh will be used for supporting the cavern sidewalls.

The cavern sidewalls are anticipated to move inward up to about 25 mm (1 in.) on each side due to high horizontal stresses, based on FLAC 3D/UDEC numerical modeling. Over-stressing is expected in the ground immediately above the cavern crown. Ground displacements will be monitored during excavation and will include several multipoint borehole extensometers installed from the surface and terminating just above the cavern crown.

Forest Park intake

The Forest Park intake is one of the largest tangential vortex intake structures ever designed. The intake will transfer flow from the existing Forest Park tubes down to tunnel elevation. The existing tubes are a pair of 8.8-m (29-ft) horseshoe-shaped tunnels that were constructed by cut-and-cover in the early 1900s, as well as a 4.9-m (16-ft) horseshoe-shaped tunnel. Downstream of the tubes, the River Des Peres has been channelized.

The Forest Park intake includes a diversion structure located in the channel of the River Des Peres. From the diversion structure, flow drops and enters an approach channel and inlet structure. The inlet structure is a tangential vortex that directs flow to a dropshaft. At the base of the dropshaft is a large deaeration chamber,

FIG.4

Profile of pump station cavern.

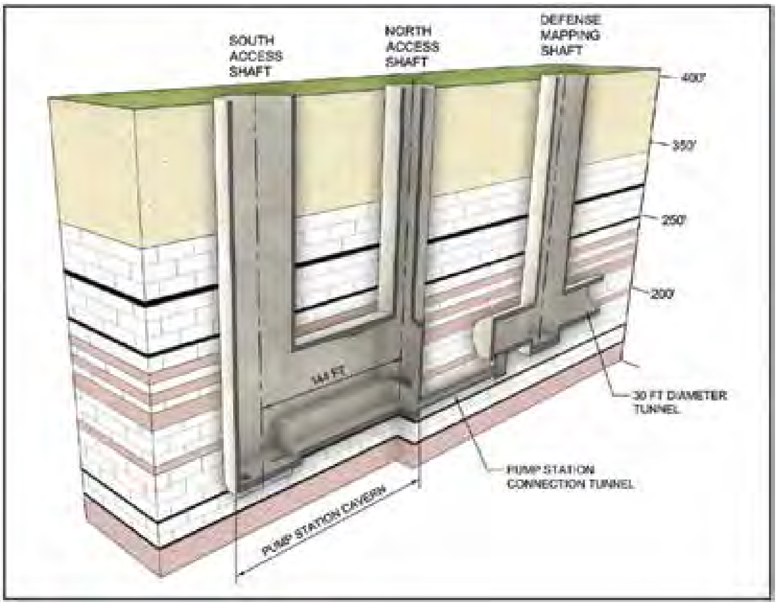
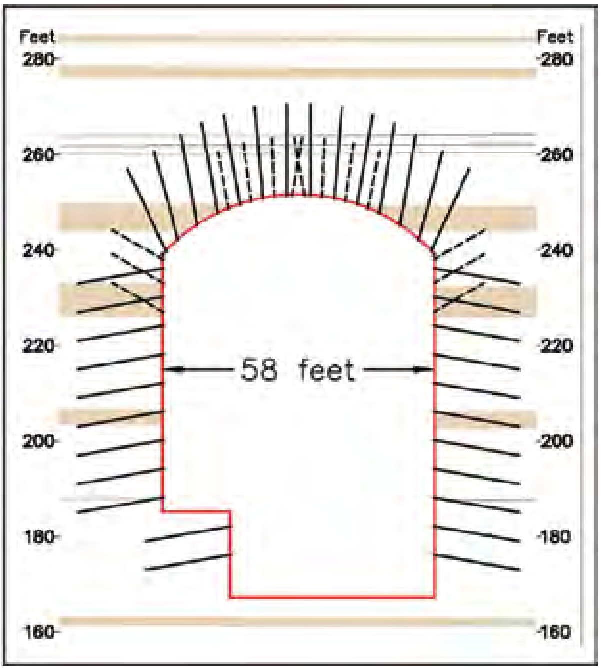


FIG.5

Cross section of pump station cavern.



located immediately upstream of the Macklind Shaft. Figure 6 shows the general arrangement of the Forest Park intake.

The hydraulic performance of the Forest Park intake was initially modeled using computational fluid dynamics (CFD) to confirm that it could convey the peak design inflow. CFD modeling was followed by construction of a 1/16 scale physical model to further evaluate the hydraulic characteristics and determine final dimensions and configuration. Construction of the inlet structure and approach channel will require excavating a deep slot, up to about 30 m (100 ft) below grade in the south slope of the River Des Peres channel. Initial ground support will consist of secant piles in the soil zone and a combination of rock dowels, welded wire mesh and shotcrete in the bedrock.

Other facilities

The project includes almost 3,400 m (11,000 ft) of drill-and-blast tunnels and deaeration chambers to connect dropshafts to the TBM tunnel. About half of this length will be intake tunnels having a minimum excavated diameter sufficient to install 1.8-m (6-ft) diameter fiberglass pipe. The remainder of the deaeration chambers and larger diameter Glaise Creek, Rock Creek and Wherry Creek tunnels will be lined with cast-in-place concrete. Initial support systems for the drill and blast tunnels and deaeration chambers consist of rock dowels, welded wire mesh and shotcrete in Type A and B ground and steel ribs in Type C ground.

A 6.1-m (20-ft) diameter emergency overflow shaft will be located near the downstream end of the TBM Tunnel. Although each of the intakes is equipped with slide or roller gates that can be closed when complete filling of the tunnel is expected, an emergency overflow is included in the system in case of gate failure. Of particular concern are the gates at the Forest Park intake and the other three large intakes, which contribute the majority of the inflow.

The dropshafts and vent shafts for all except the largest intakes will be excavated using either raise boring or blind boring techniques. The choice of construction technique will be left to the contractor. The dropshaft for the Forest Park intake is expected to be blasted before lining with concrete. The main ventilation shafts on the TBM Tunnel alignment, located at the River Des Peres Park shaft and Macklind shaft, will also be blasted and lined with concrete.

Construction schedule and cost estimate

Construction of the LMRDP Tunnel is expected to take about six and a half years. The contractor will begin construction at the Defense Mapping site, sinking not only the launch shaft, but also the north and south access shafts for the pump station cavern. Shot rock and tunnel muck will be processed and placed on the site to complete its filling.

Excavation of the TBM Tunnel and the cavern can take place simultaneously. At the three-year mark, the tunnel contractor will demobilize from a portion of the site to allow the pump station contractor to begin work. By this point, TBM excavation is expected to be complete and the tunnel contractor will have demobilized his muck processing equipment from the site. The pump station contractor will begin with lining the cavern and its two access shafts.

After 54 months, the tunnel contractor must completely vacate the site to allow the pump station contractor to install screening equipment in the launch shaft and to complete build-out. By this point, concrete lining of the section of tunnel extending from the Defense Mapping shaft to the River Des Peres Park shaft is expected to be complete. The tunnel contractor will move his tunnel construction water pumping station up to the emergency overflow shaft, and lining of the section of tunnel upstream of the River Des Peres Park shaft can take place.

The final six months of the schedule is used for intake activation. This work must be coordinated with the pump station contractor and the waste water treatment plant operator. In cooperation with and at the direction of both the pump station contractor and MSD, the tunnel contractor will activate each of the individual intakes.

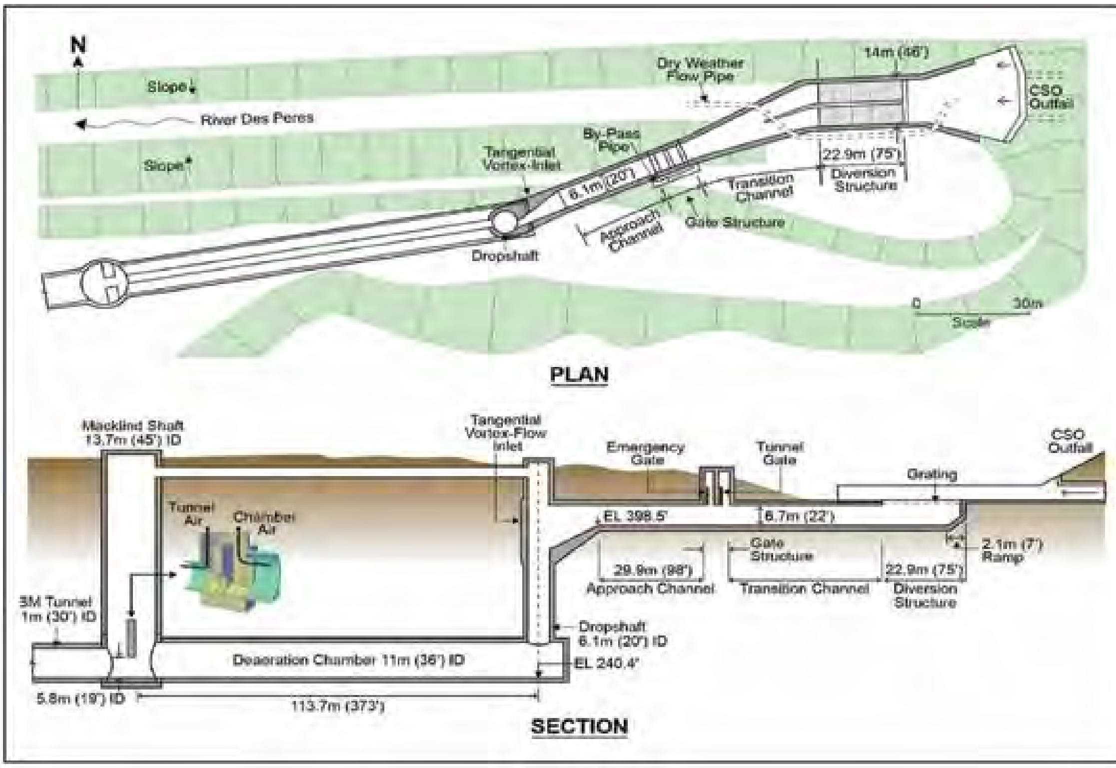
The Opinion of Probable Construction Cost, prepared at the 95 percent design stage in mid-2017, totaled $585 million in current dollars. Of that cost, roughly $48 million was carried as contingency.

Summary

The Metropolitan St. Louis Sewer District has completed design of the LMRDP CSO Storage Tunnel, which is the largest component of its consent decree driven Project Clear. The work included modeling and

FIG.6

General arrangement of Forest Park intake.



design of one of the largest tangential vortex intakes ever, design of a deep, large diameter hard rock tunnel, and design of excavation and initial ground support for a large, cavern-style dewatering pump station. At an estimated cost of $585 million, the tunneling project is expected to require six and a half years for construction, including activation. ■

Acknowledgments

The authors would like to acknowledge Jack Raymer, the primary author of the project's Geotechnical Baseline Report, for providing input and figures related to ground conditions and initial support.

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Klecan, W., Pride, P., Hallsten, J., Craig, A., Lyons, T. and Kharazi, A., 2017. Diverting 4400 MGD into a Deep CSO Tunnel: Forest Park Intake Design. In WEFTEC 2017 Proceedings of the Water Environment Federation, Chicago, IL: WEF.

Breakthrough at the Galerie des Jantos tunnel overcomes multiple caverns

In April 2019, a Robbins 3.5-m (11.5-ft) diameter main beam tunnel boring machine (TBM) broke through into open space, completing its 2.8-km (1.7-mile) long tunnel. It was not the first time the machine had encountered open space. Twice during tunneling, the machine hit uncharted caverns, the largest of which measured a staggering 8,000 m³ (283,000 cu ft) in size.

"The obstacles overcome at the recent breakthrough are a significant achievement," said Marc Dhiersat, project director of the Galerie des Janots tunnel for contractor Eiffage Civil Construction. "We are proud to have led a motivated and conscientious team to the end of the tunnel who worked well without accidents despite the many technical difficulties encountered."

The water tunnel, located below the community of Cassis, France, is an area of limestone known for its ground water, karstic cavities and voids. The limestone, combined with powdery clays, made for difficult excavation after the machine's March 2017 launch. At the 1,035-m (3,395-ft) mark, the crew hit a cavern on the TBM's left side. The cavern, studded with stalactites and stalagmites, was grazed by the TBM shield. The crew had to erect a 4-m (13-ft) high wall of concrete so the TBM would have something to grip against. The TBM was then started up and was able to successfully navigate out of the cavern in eight strokes without significant downtime to the operation — the process took about two weeks. Despite the challenges, Dhiersat thought positively of the TBM throughout the ordeal, "This has been the best machine for the job due to all the geological difficulties."

The first cavern, encountered at the 1,035-m (3,395-ft) mark, was grazed by the TBM shield on one side and was studded with stalactites and stalagmites.

The first cavern, while the largest, was not the most difficult void encountered. The machine was averaging 20 to 22 m (65 to 72 ft) advance per day in two shifts after clearing the first cavity, with a dedicated night shift for maintenance. While excavating, a combination of probe drilling and geotechnical BEAM investigation — a type of electricity-induced polarization to detect anomalies ahead of the TBM — were used. Crews ran the excavation five days per week, achieving more than 400 m (1,310 ft) in one month. This performance continued until the 2,157-m (7,077-ft) mark, when the machine grazed the top of an unknown cavity that extended deep below the tunnel path. The structure measured 22-m (72-ft) long, 15-m (49-ft) wide, and 14-m (46-ft) deep, or about 4,500 m³ (159,000 cu ft) of open space.

Crews probed in front of the cutterhead and began work to stabilize and secure the cavity with foam and concrete, as well as excavate a bypass gallery. "After filling much of the cavity (1,500 m³ or 53,000 cu ft), our biggest difficulty was to ensure the gripping of the machine. We needed six bypass galleries and four months of work to reach the end of this challenge," said Dhiersat. For the last 600 m (2,000 ft) of tunneling, "we were finally in good rock," he emphasized. Overall rates for the project averaged 18 m (59 ft) per day in two shifts and topped out at 25 m (82 ft) in one day.

"The cooperation with Marc and his team on site was very good, and we always enjoyed their professionalism and commitment to the project and the task. This, without any doubt was key for the success we achieved," said Detlef Jordan, business manager Robbins Europe. "For us, it was satisfying and motivating to see that, by working together and joining the efforts of all partners on the project, the best and most successful outcome can be achieved. This commitment for decades has been at the heart of success in the tunneling industry, but it has not always been observed on other recent projects."

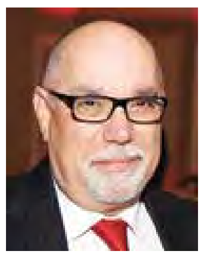
Galerie des Janots is one of 14 operations designed to save water and protect resources, which are being carried out by the Aix-Marseille-Provence metropolis, the water agency Rhône Mediterranean Corsica, and the state government. The Janots gallery, once online, will replace existing pipelines currently located in a railway tunnel. These original pipes have significant deficiencies with estimated water losses of 500,000 m³/a (132 million gal/year). The new tunnel will increase capacity to 440 L/s (116 gal/second). ■

Personal News

R. MARK DEMPF, PE, ENV SP, has joined McMillen Jacobs as a principal and vice president in the Construction Management practice based in the New York, NY (NYC) office. In this role, he will support existing tunnel and underground design and construction projects and participate in new project pursuits. These include projects for existing clients such as the NYC Department of Design and Construction (DDC) and the NYC Department of Environmental Protection, as well as new clients such as the NYC Economic Development Corp., the Port Authority of New York and New Jersey, the Passaic Valley Sewer Commission, and other water and sewer utilities in the New York metropolitan area. Dempf is a licensed professional engineer in New York and Vermont with 33 years of experience in infrastructure/utility master planning, design and construction activities.


DEMPF

The Deep Foundations Institute (DFI) has formed its 26th technical committee, the DFI Risk and Contracts Committee. The goal of the committee is to raise awareness of risk management through programs and promotion. The committee's first project is to research and produce *The Book of Risks for Geotechnical Projects* covering internal risks, legal risks, external risks and geotechnical-exploration risks. The chair of the new DFI committee is **ALEXANDER FILOTTI,** MBA, PE, risk controller of Underpinning and Foundation Skanska Inc. Filotti has 19 years of experience with engineering work and technical development related to deep-foundation projects as well as the development of computer 3D modeling applications for deep foundation projects. His current activity focuses on risk management and ethics, and he teaches the Design of Foundations course at Hofstra University School of Engineering and Applied Science. The vice chair of the committee is **RICHARD D. KALSON**, a partner in the Construction Law Group of Benesch. Kalson is well-versed in deep-foundation construction projects and contracts as risk management tools. He provides counsel to subcontractors, suppliers and project owners in litigation and business consultation matters, including many ENR 400 contractors and ENR 600 specialty contractors, on all phases of the construction process on projects throughout the United States. ■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Women In Tunneling

Women In Tunneling is now affiliated with UCA of SME

The Underground Construction Association (UCA) Division of SME is pleased to announce the addition of Women in Tunneling (WIT) as an affiliate to the association. The affiliation will provide WIT members with a broader base of industry and technical knowledge through professional publications, topical conferences, career services and the online reference library onetunnel.org.

At a luncheon during the 2018 North American Tunneling conference in Washington, D.C., the Women in Tunneling discussed the idea to affiliate with the UCA of SME and received a positive endorsement. "UCA of SME looks forward to partnering with WIT for the benefit of the tunneling community," said Melanie Penoyar-Perez, SME Director of Operations. "More and more women are being drawn to tunneling and this diversity of thought and talent is needed to drive innovation in the industry. In partnership with WIT, UCA of SME looks forward to providing networking and professional development opportunities for women at its future conferences and events."

WIT at RETC

The next annual meeting of the WIT will be at the Rapid Excavation and Tunneling Conference (RETC) in Chicago, IL June 16-19, 2019. WIT will host a reception on Sunday, June 16 from 6-8 at the Hyatt Regency Hotel.

Additionally, industry members can join in their discussions on their new SME Community page, Women in Tunneling.

Or follow their LinkedIn group and Facebook page, Women in Tunneling, #womenwhotunnel. They feature a woman in the industry and her career path each month. Be sure to welcome these new members while attending RETC. ■

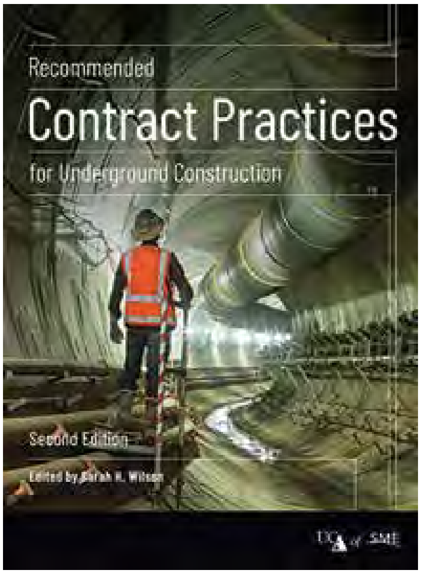
New Media

Recommended Contract Practices for Underground Construction

2019, second edition edited by Sarah H. Wilson, published by SME, 12999 E. Adam Aircraft Cir., Englewood, CO 80112, USA, www.smenet.org/store, email books@smenet.org, phone 303-948-4225, 800-763-3132 x225, 232 pp, softcover, ISBN 978-0-87335-459-2, $89 member, $69 student member, $139 list. Also available as an ebook.

A successful underground project is one where relationships are strong, the objectives as understood by each party are met or exceeded, and the work product serves its stakeholders and is maintainable in a way that fits with the project vision. High-level metrics for project success relate to safety, quality, schedule and budget.

The first edition of *Recommended Contract Practices for Underground Construction* has become a valued resource for the underground industry, serving as a concise guide for the drafting and implementation of contract provisions. It provided improvements to underground contracting practices during all project stages, and clear roles and responsibilities for project participants to promote better contracts.



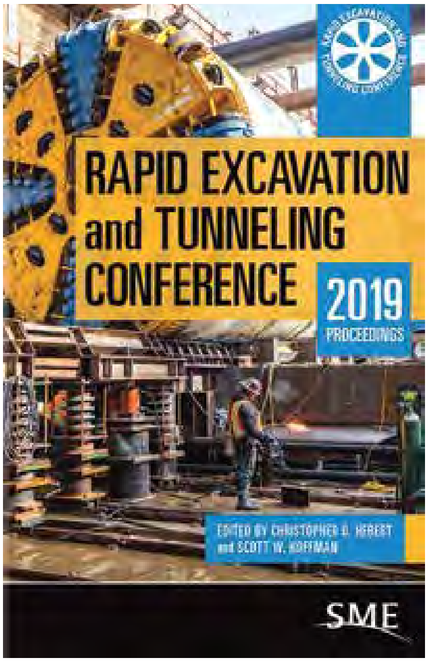
This second edition was undertaken by the UCA of SME because the industry has undergone numerous changes over the last decade. Changes in tunneling technology, more common use of design-build as a contracting mechanism and the many lessons learned have sparked some creative contract approaches.

The recommendations contained in this edition are intended to guide owners and their engineers in developing and administering contracts and to give contractors a better understanding of the rationale behind contract provisions. The goal is that more underground projects in this country can be best projects, where improved relationships and fair contracts enable all project participants to personally invest in cost-effective, profitable projects, ensuring the continued health of the underground industry. ■

Rapid Excavation and Tunneling Conference: 2019 proceedings

2019, edited by Christopher D. Hebert and Scott W. Hoffman, published by SME, 12999 E. Adam Aircraft Cir., Englewood, CO 80112, USA, www.smenet.org/store, email books@smenet.org, phone 303-948-4225, 800-763-3132 x225, 1,280 pp, hardbound, ISBN 978-0-87335-470-7, $149 member, $129 student member, $219 list. Also available as an ebook.

Every two years, industry leaders and practitioners from around the world gather at the Rapid Excavation and Tunneling Conference (RETC), the authoritative program for the tunneling profession, to learn about the most recent advances and breakthroughs in this unique field. The information presented helps professionals keep pace with the ever-changing and growing tunneling industry. This book includes the full text of 111 papers presented at the 2019 conference and covers such topics as contracting practices, design and planning, geotechnical considerations, hard-rock tunnel boring machines, new and innovative technologies, pressure-face TBM case histories, and tunneling for sustainability. The papers will inform, challenge and stimulate each reader.



The proceedings includes chapters on contracting practices and cost, design and planning, design/build projects, difficult ground, drill and blast, environment, health, and safety, future projects, geotechnical considerations, ground support and final lining, grouting and ground modification, hard-rock TBMs, large-span tunnels and caverns, new and innovative technologies, pressure face TBM case histories, pressure face TBM technology, SEM/NATM, shafts and mining and tunneling for sustainability. ■

CSM Short **Course**

CSM offers tunneling short course

Registration is open for the Colorado School of Mines' (CSM) Tunneling Fundamentals, Applications and Innovations short course, Oct. 14-17, 2019. Last year's course sold out with more than 150 participants. View the full agenda or reserve your spot by registering at http://underground.mines.edu.

Tunneling is booming. Forecasts show tremendous growth in tunnel projects over the next decade — water and wastewater, transportation, energy, utilities and hyperloops, and the CSM course is the way to boost your knowledge.

The comprehensive four-day agenda includes topics ranging from planning to design to construction of tunnels for all purposes and across all types of ground conditions. Technical leaders from across the tunneling industry will teach key principles and the latest innovations. Numerous upcoming U.S. and international tunneling projects will be highlighted. Five owner-representatives will provide insights into the industry, and CSM faculty and students will share the latest research and development innovations.

Offered by CSM's Center for Underground Construction and Tunneling, the tunneling short course capitalizes on the state-of-the-art labs and facilities at the school, giving attendees a unique opportunity to interact with the most sophisticated and innovative technologies in the tunneling industry. Hands-on labs and workshops each afternoon offer knowledge through learning by doing.

There will also be networking opportunities, industry-to-industry as well as with the many students studying to enter the industry. By learning from and speaking with key firms, contractors and engineers about the biggest projects of our time, the goal of the short course is for participants to get a clear picture of where this fast-paced and dynamic industry is heading.

The Colorado School of Mines Center for Underground Construction and Tunneling is a collaborative, multi-disciplinary group of faculty and students from the departments of civil engineering, geology and geological engineering, mechanical engineering, mining engineering, geophysics and computer science, with a collective interest in education and research in underground engineering.

For more information about the Colorado School of Mines, visit www.mines.edu. ■

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TUC Tunnel Demand Forecast

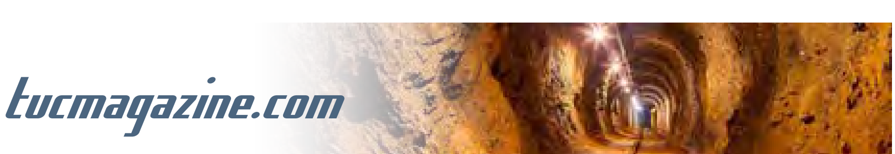
COMPILED BY JONATHAN KLUG, DAVID R. KLUG & ASSOCIATES

TUNNEL NAME	OWNER	LOCATION	STATE	TUNNEL USE	LENGTH (FEET)	WIDTH (FEET)	BID YEAR	STATUS
Gateway Tunnel	Amtrak	Newark	NJ	Subway	14,600	24.5	2021	Design study
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
Cross Harbor Freight Tunnel	NYC Reg. Develop. Authority	New York	NY	Rail	25,000	30	2022	Under study
Redundancy Tunnel Program - Northern	Boston MRWA	Boston	MA	CSO	23,760	10	2026	Under study
Redundancy Tunnel Program - Southern	Boston MRWA	Boston	MA	CSO	50,160	10	2028	Under study
Narragansett Bay CSO Phase III - Pawtucket Tunnel Conveyance Tunnel	Narragansett Bay Commission	Providence	RI	CSO	13,000 8,800	28 10	2020 2024	Under design 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	Under design
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	2020	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
Westerly Main Storage Tunnel	NEORSD	Cleveland	OH	CSO	12,300	24	2018	JayDee/ Obayashi awarded
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
ALCOSAN CSO Ohio River Allegheny River Mononghahela River	Allegheny Co. Sanitary Authority	Pittsburgh	PA	CSO	10,000 41,700 53,900	30 30 30	2021 2022 2023	Under design Under design Under design
I-75 modernization project	Michigan DOT	Detroit	MI	CSO	22,000	14	2018	Oakland Corridor awarded
Enbridge Line 5 Tunnel	Enbridge	Traverse City	MI	Oil	23,760	12	2020	Under study
I-70 Floyd Hill Highway Tunnel	Colorado Dept. of Transportation	Denver	CO	Highway	15,840	60x25	2022	Under design

T&UC Tunnel Demand Forecast

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
W-6: Highway 90 to SW Military Drive	San Antonio Water Systems	San Antanio	TX	Sewer	28,000	10	2020	Under design
D2 Subway - 2nd Light Rail Alignment	Dallas Area Rapid Transit	Dallas	TX	Highway	3,000	22	2020	Under design
I-70 Floyd Hill Highway Tunnel	Colo. Dept. of Transportation	Denver	CO	Highway	15,840	60x20	2022	Under design
Ship Canal Water Quality Project	Seattle Public Utilities	Seattle	WA	CSO	14,250	19	2018	Under design
West Seattle to Ballard Extension	Sound Transit	Seattle	WA	Transit	10,500	18	2022	Under design
L.A. Metro Westside Phase 2 Phase 3	Los Angeles MTA	Los Angeles	CA	Subway	26,500 26,500	20 20	2016 2018	Tutor Perini/O&G JV awarded Frontier-Kemper/ Tutor/Perini awarded
Speulvada Pass Corridor	Los Angeles MTA	Los Angeles	CA	High/Trans.	55,500	60	2020	Under study
River Supply Conduit - Unit 7	LA Dept. of Water and Power	Los Angeles	CA	Water	13,500	12	2018	Frontier-Kemper awarded
JWPCP Effluent Outfall Tunnel project	Sanitation Districts of LA	Los Angeles	CA	Sewer	37,000	18	2018	Dragados USA low bidder
Freeway 710 Tunnel	CALTRANS	Long Beach	CA	Highway	26,400	38	2021	Under design
BDCP Tunnel #1 BDCP Tunnel # 2	Bay Delta Conservation Plan	Sacramento	CA	Water	26,000 369,600	29 35	2018 2019	Under design Under design
SVRT BART	Santa Clara Valley Trans Authority	San Jose	CA	Subway	22,700	20	2019	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	Under design
Coxwell Bypass Tunnel program	City of Toronto	Toronto	ON	CSO	35,000	12	2018	JayDee/Michels/C&M McNally 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
Taylor Massey Tunnel	City of Toronto	Toronto	ON	CSO	20,000	18	2018	Under design
Inner Harbour West	City of Toronto	Toronto	ON	CSO	18,400	19	2021	Under design
Scarborough Rapid Transit Extension	Toronto Transit Commission	Toronto	ON	Subway	25,000	18	2018	Under design
REM Transit Tunnel	City of Montreal	Montreal	QC	Subway	27,000	22	2017	SNC/Dragados/ Aecon JV Awarded
Green Line LRT	City of Calgary	Calgary	AB	Transit	26,250	20	2018	Under design
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	Awaiting award
Broadway Sky train	Trans Link	Vancouver	BC	Subway	25,000	18	18	Under design
Northern Gateway Hoult Tunnel	Enbridge Northern	Kitimat	BC	Oil	23,000	20	2014	Under design



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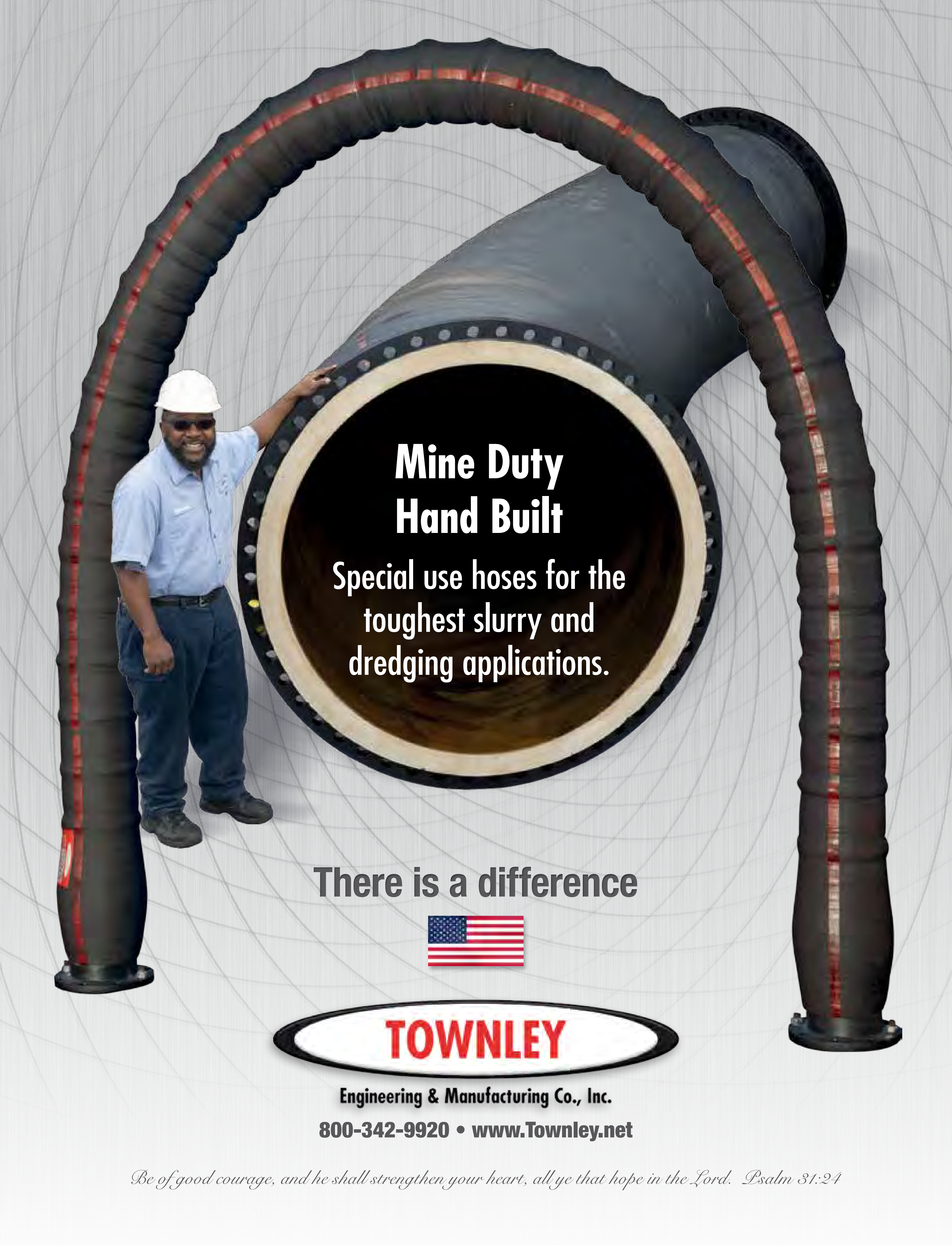
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