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2014 Outstanding Underground Project

Robinson Creek Tunnel Fire

By Randy Zeiger, Gabrielle Cadieux, Denis Laviolette, Nick Laviolette, Justin Laviolette, and Edward D. Sparks II

On the eve of Saturday, April 26, 2014, an arson fire engulfed a CSX Transportation railroad tunnel near Robinson Creek, KY, cutting off service to two active coal mines in the area. The biggest and most productive mine is TECO Coal in Myra, KY, which employs approximately 500 personnel, and produces around 2 million tons (1.8 million metric tonnes) of coal per year. Normal track speed for this branch line is 25 mph (40 kph), and train traffic consists of two to three coal trains per week. The tunnel is 742 ft (226 m) in length, most of which was timber lined.

When ignited, the coal seams that outcropped in the tunnel roof and walls, along with the creosote-laden timbers and ties that lined the tunnel, effectively turned the tunnel into an oven, causing much of the walls and roof to collapse. The timber lining system burned for several days before both of the portals were able to be plugged with fill material to suffocate the fire and to address community air quality concerns (refer to Fig. 1).

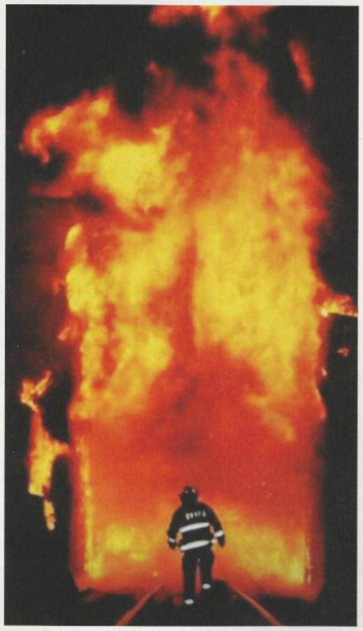


Fig. 1: Scene of the fire at the west portal on April 26, 2014
(Photo credit: Pike County, KY, newspaper)

CSX Transportation responded to this emergency, focusing on safely restoring service to their customers. This task was wrought with various technical, environmental, and health and safety challenges, including firefighting, managing air quality, and reducing personnel risks while working in a hazardous work environment. AMEC was asked by CSX Transportation to respond to this emergency. AMEC worked with CSXT's Engineering and Environmental departments, HAZMAT, local Division personnel, and LRL Construction Company to manage the incident, address environmental concerns, evaluate the tunnel, and restore rail traffic. HEPACO provided environmental remediation and firefighting expertise. LRL Construction Company performed tunnel exploration and remedial repairs.

The AMEC tunnel engineering design team concluded that an "exploratory investigation" was needed once the fire was brought under control to assess tunnel conditions and determine what was needed to return the tunnel to full service.

Originally, the plan was to remove the earthen plugs at the portals and advance back through the tunnel using a "top heading" approach with hand scaling and rock bolting of the tunnel roof and arches to assess the condition of the tunnel interior. However, the extent of the damage and air quality issues caused by the fire did not permit this type of advance. Temperatures upwards of 3000°F (1650°C) were recorded in the debris pile along the invert of the tunnel, which was up to 15 ft (4.6 m) thick in some places. The debris had to be "mucked" out of the invert to safely advance. This presented a significant challenge due to the extreme temperatures and dangerous atmospheric conditions. With coal seams continuing to burn, it was difficult to create the proper ventilation needed in the tunnel for workers to progress. Fresh air was forced into the tunnel from one portal and withdrawn from the other. The exhaust smoke was routed through a field-fabricated "scrubber" to remove particulate matter before discharge to the environment.

As crews advanced into the tunnel, shotcrete was used to establish the initial structural support and safely assess the condition of the tunnel interior (refer to Fig. 2).

LRL advanced through the tunnel in about 30 ft (9 m) long reaches. This was done by pulling invert muck back toward the open portal with a trackhoe and removing it with a front loader (refer to Fig. 3). Crews then moved forward safely scaling the roof and sidewalls. When ground temperatures and air quality conditions allowed, ACI Certified Nozzlemen placed shotcrete on the ceiling/walls with hand nozzles and a robot to establish initial support. When applied to the coal seams, the shotcrete effectively halted degassing and extinguished visible flare-ups. The high temperatures and CO levels within the tunnel diminished as the shotcrete was applied. As workers cooled down the muck pile and hydroscaled the ceiling and walls, the ground kept "popping" due to rapid cooling. The shotcrete significantly slowed down the cooling process of the rock, and enabled workers to safely press on. LRL workers used an offtrack rubber tire shotcrete operation for the exploration phase because the rail inside the tunnel was deformed. Equipment included a robot tractor mounted arm manufactured by Shotcrete Technologies, a batch plant, and a concrete pump. LRL and the balance of the project team worked 24 hours a day for 24 days to complete this exploration. In this time, LRL installed three-hundred thirty-two 8 ft (2.4 m) long CT-bolts supplied by DSI Underground and placed 100 yd^3 (76 m^3) of shotcrete.

Based on the findings from the exploration, the tunnel engineering design team developed a final liner solution that involved additional rock bolts and shotcrete. Once initial roof support was installed, CSXT crews replaced the track through the tunnel and resumed revenue rail service to the mines on June 10, 2014. Then LRL worked around rail traffic using its rail-mounted shotcrete operation for final liner construction.

LRL was able to place 100 yd^3 (76 m^3) of shotcrete per 12-hour shift. LRL loaded 50 yd^3 (38 m^3) of shotcrete onto their shotcrete train, mobilized 1/4 mile (1/2 km) to the tunnel, placed 50 yd^3 (38 m^3) of shotcrete, flushed hoses, cleaned out the pump, and then cleared the track for a coal train to pass. This process was repeated two times per shift. Final liner construction took approximately 2 weeks. A total of one-hundred seventy-five 13 ft (4 m) and three-hundred seventeen 8 ft (2.4 m) long CT-bolts and 1270 yd^3 (970 m^3) of shotcrete were installed in the tunnel. The shotcrete included 80 lb/yd^3 (47 kg/m^3) of steel fiber reinforcement and yielded a 28-day unconfined compressive strength of 6000 psi (41 MPa).

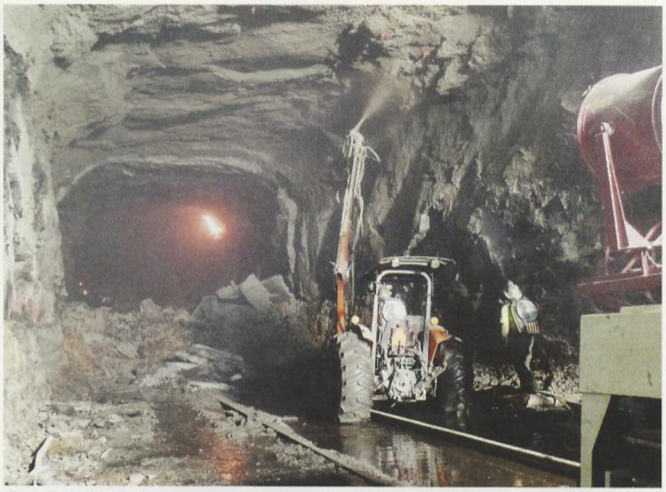


Fig. 2: Initial shotcrete roof support

Fig. 3: Muck removal with loader

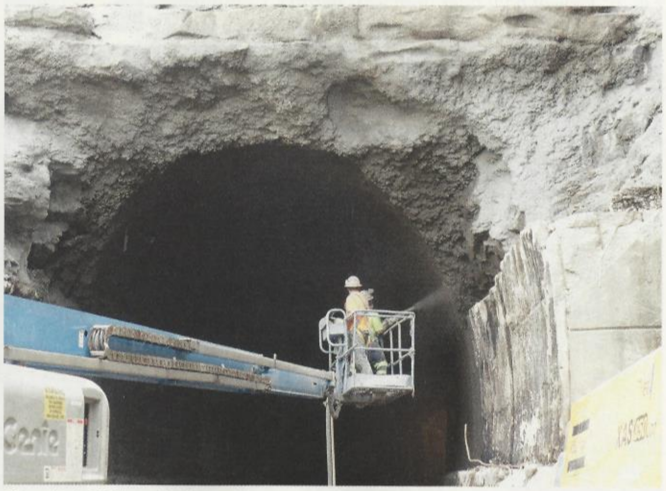


Fig. 4: ACI Certified Nozzleman applying shotcrete to east portal

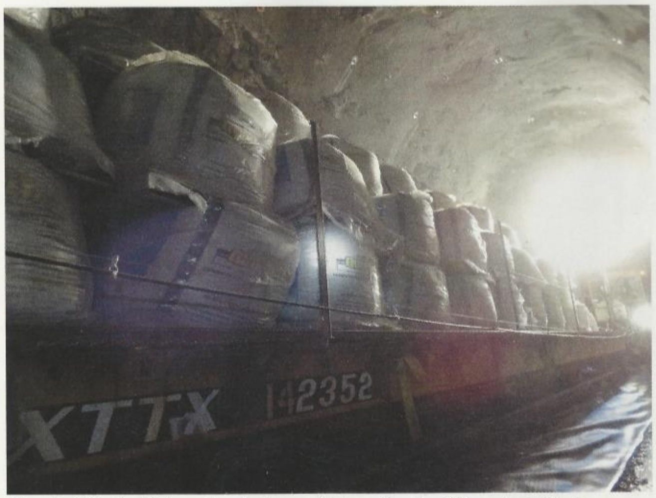


Fig. 5: Fifty bulk bags loaded on a flat car for final liner installation

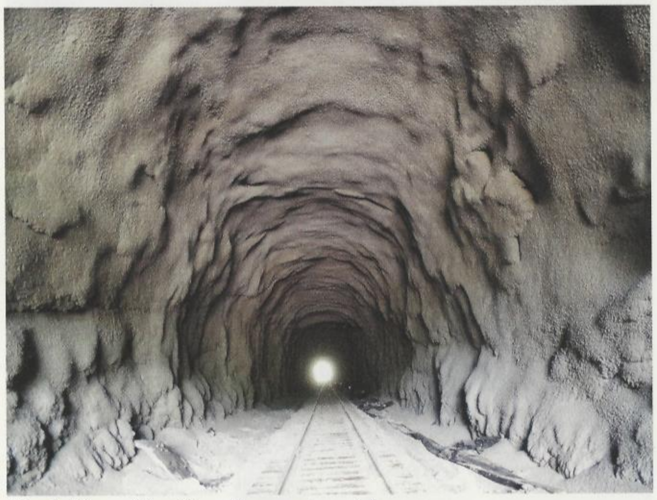


Fig. 6: View of final liner from west portal

The QUIKRETE Companies supplied premixed 3000 lb (1360 kg) bulk bags for this project. A total of 1370 bulk bags were used to complete both phases of this project. Using the premixed bulk bags for a job of this caliber guaranteed the materials were uniform and to contract specifications.

Use of the aforementioned construction techniques and materials resulted in rail service restoration 45 days after the fire and full project completion 10 days later. The final product is a reliable, sound tunnel that will support vital railroad service for many years to come (refer to Fig. 4 through 8).

The Outstanding Underground Project

Project Name
Robinson Creek Tunnel Fire

Project Location
Robinson Creek, KY

Shotcrete Contractor
LRL Construction Co. Inc.*

General Contractor
LRL Construction Co. Inc.*

Architect/Engineer
AMEC*

Material Supplier/Manufacturer
The QUIKRETE Companies,*
Shotcrete Technologies*

Project Owner
CSX Transportation

*Corporate Member of the
American Shotcrete Association

Fig. 7: West portal—final liner

Fig. 8: East portal—final liner

2014 Outstanding Repair & Rehabilitation Project

The 606-Bloomingdale Trail | Viaduct Repairs

By Kevin Doyle

Located on the northwest side of Chicago, IL, the abandoned railway known as the Bloomingdale Line, originally constructed in 1873, runs east and west through four dense neighborhoods including Bucktown, Logan Square, Wicker Park, and Humboldt Park. The line starts at the Kennedy expressway, just north of the loop, half way between Wrigley Field and US Cellular Field, and heads west for 2.67 miles (4.29 km). The line was built shortly after the Chicago fire in 1871 by Chicago and Pacific Railroad to connect outlying rail ports to the Chicago River and to help support the city's expanding industrial sector. Due to a high number of accidents involving trains and residents all over the city in the late 1800s, the city passed an ordinance mandating that all rail lines in the city be elevated and, in 1910, the Bloomingdale Line was raised to 15 ft (4.6 m) above street level.

Use of the line greatly reduced in the 1980s and train service was eventually rerouted to other rail lines. By the mid-1990s, all rail activity ceased, creating an ideal platform for an elevated rails-to-trails conversion. The out-of-service rail line was largely left alone and reclaimed by wildlife and plants. The idea for "The 606" has its origins in the CitySpace Plan of 1998, which showed the Logan Square community area did not meet minimum standards for open space per capita. In fact, of the 77 community areas, it ranked second to last at 99 acres (40 ha) deficient for the population. In 2004, the City of Chicago adopted the Logan Square Open Space Plan, which helped identify ways to increase open space to achieve the minimum standards. The Bloomingdale Line was called out as a way to provide open space in an otherwise dense and built-out community.

The City of Chicago and the Chicago Park District, with the support of local residents and The Trust for Public Land, proposed to officially repurpose the elevated tracks into a 2.67 mile (4.29 km) long recreational trail for biking, running, and walking. "The 606" refers to the park and trail system that is currently under construction, the centerpiece of which is the Bloomingdale Trail. "The 606" gets its name from the zip code prefix, 606, which all Chicagoans share; the Bloomingdale Trail is named for the street right-of-way where the trail is located. The proposal encompassed structural concrete repair and rehabilitation work of 36 concrete bridges and retaining walls, landscaping, bridge deck waterproofing, new bridge construction, decorative guardrail, new lighting and security cameras, the creation of new parks, and installation of numerous access ramps along the length of the trail.

The project was let out to bid early May 2013, bid late in May 2013, and awarded shortly thereafter, demonstrating the urgency the City had to get this project under way. American Concrete Restorations (ACR) was contracted to repair the bridges and retaining walls following the Chicago Department of Transportation Structural Repair of Concrete Specification, which gives the contractor a choice of formed concrete repair or shotcrete. Due to the need for extensive coordination with the surrounding communities, ACR was finally called upon to begin work in late October 2013.

With frost already present and frigid cold temperatures soon to be upon Chicagoland, ACR devised a plan to keep the project moving forward through the winter months. This plan consisted of performing the necessary concrete removals at the bridge locations followed by fully enclosing and heating the structures for shotcrete work to proceed. Along with a late start in the year and the cold weather setting in quickly, this project had a variety of obstacles, including access into heavily congested neighborhoods and residents' properties, repairs during limited closures of main thoroughfares, and a structure that was in much worse shape than originally anticipated (Fig. 1).

Shotcrete Segment of Project Overview

The shotcrete portion of "The 606" was located at each of the 36 bridges and also the retaining walls and caps that spanned the 2.67 miles (4.29 km) of the project on the north and south sides of the trail. Work at the bridge locations encompassed the entire substructure including the wing walls, abutments, columns, and parapets. Each of the 36 bridges crossed two-lane streets, had three piers, and 15 columns. The trail also crossed five arterial streets, each with four lanes of traffic. At these locations there were four piers and 20 columns. At the longest bridge crossing, Humboldt Park Boulevard, it crossed six lanes of traffic, and there were 11 piers and 33 columns (Fig. 2).

Challenges

Upon commencement of the project, ACR realized that the bridges were in far worse condition than shown on the plans. Quantities immediately began increasing, as did the depths of the repairs, due to the fact that these walls were constructed with 1 in. (25 mm) unwashed river rock aggregate and without reinforcing steel. It was imperative to maintain excellent communication with the general contractor and the owner's engineers to verify work to be done and any additional repair steps to be taken, such as the addition of reinforcing bar, shoring, and identifying areas of complete deterioration requiring full replacement.

Because all the bridges are in close proximity to residences, schools, daycare centers, parks, dog parks, small businesses, and main thoroughfares, some special precautions had to be taken to protect private property and also to protect the heavy pedestrian and motor traffic that travelled through these areas. Along this 2.67 mile (4.29 km) jobsite, ACR encountered numerous neighborhoods encompassing various demographics. Many work zones were located adjacent to schools, requiring ACR to use extreme caution when conducting repairs and moving machinery in close proximity to young children who are often unaware of their surroundings and the dangers of a construction zone.

Due to the congestion of the work area and the proximity to neighboring homes, parks, and schools, ACR sandblasted with water to keep dust to a minimum. ACR also cleaned up their work area at the end of every day to prework conditions, thus leaving the neighborhood safe for pedestrians and vehicle traffic (Fig. 3).

As the bridges provided the only means of travel for residents from one side of the trail to the other, ACR had to phase its work at the bridge locations, keeping one lane of traffic and one sidewalk open at all times.

ACR encountered both winter and summer conditions during the course of the project. This change in environment called for different approaches to quality control. When starting the project in late October, the cold temperatures of the infamous 2013-2014 Chicago winter were

Fig. 1: Repair areas were found to be not only much larger in the field but also deeper than was called out on the plans and also lacking any reinforcing bar

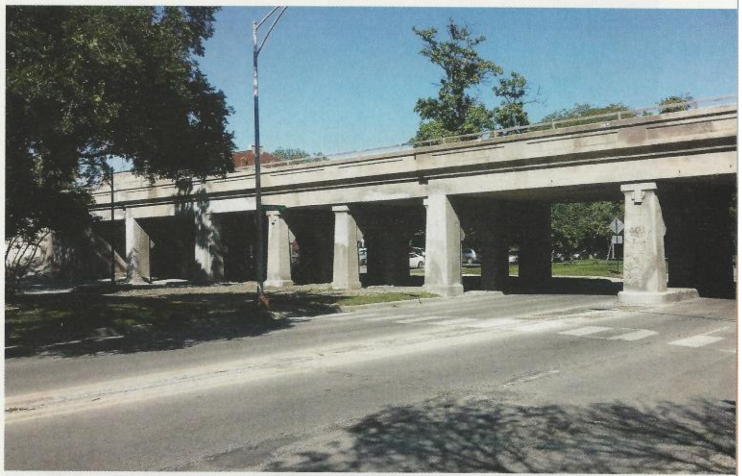


Fig. 2: Repaired 11 piers spanning 250 ft (76.2 m) over six lanes of traffic

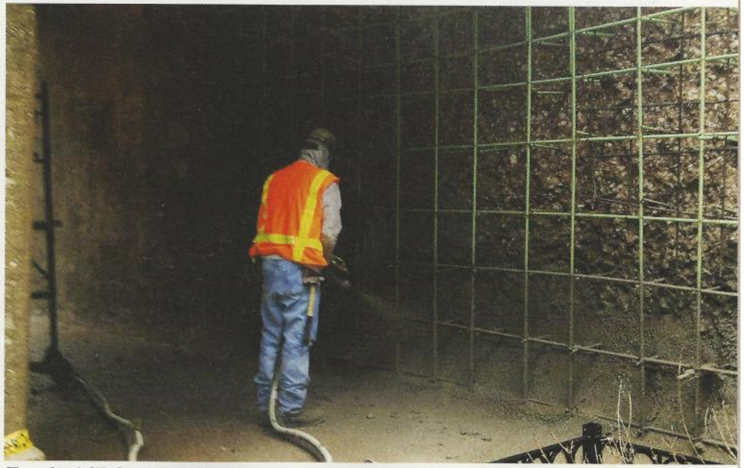


Fig. 3: ACI Certified Nozzleman shotcreting newly-reinforced repair areas

already setting in. ACR devised a comprehensive plan for dealing with the upcoming winter months to accommodate low temperatures of up to –40°F (–40°C) wind chill temperatures. Each bridge was wholly enclosed using heavy-duty, fire-retardant tarps (Fig. 4 through 6). ACR also deployed large propane heaters to ensure proper ambient and substrate temperatures. Where full road closures were necessary, ACR was allowed a maximum of 2 weeks to complete the work on the specific bridge, including 7 days for curing, to satisfy the restrictions of the City of Chicago permits for street closures. ACR also used heaters to keep the water warm for mixing and torpedo heaters to warm the skids of pre-bagged material and the staging area. ACR used both infrared and standard thermometers to confirm the temperature of the substrate, water, pre-bagged material, and mixed material stayed at or above the specified minimum temperatures. The temperatures were recorded on quality control checklists every hour to document ACR's ability to maintain a high-quality shotcrete mixture. ACR's plan succeeded in providing quality repairs while allowing the project to progress through the brutal Chicago winter.


Fig. 4: *Heated enclosures were installed on portions of bridge during winter months*

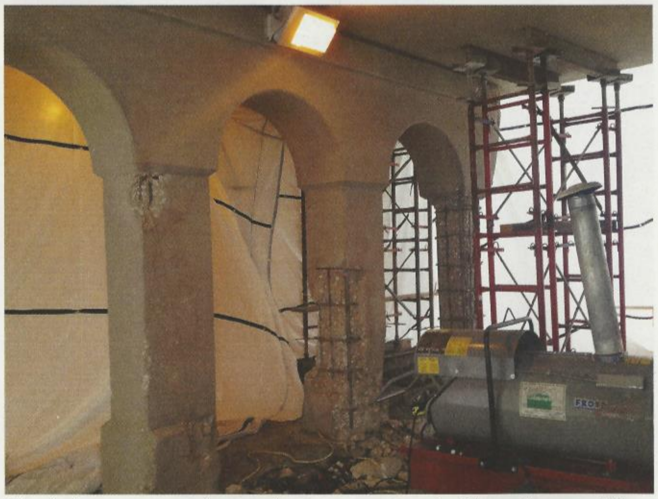


Fig. 5: *Large propane heaters kept temperatures inside enclosure within specifications during cold winter months*

Upon the arrival of the hot summer months, ACR had to pay special attention to make sure the shotcrete mixture remained at satisfactory maximum temperatures. To maintain the temperatures required in the specifications, ACR replaced the water supply midday with fresh cold water or added ice to the water supply containers. When possible, ACR's staging area along with the pre-bagged skids of material were set on the North side of the bridge next to the retaining wall to decrease the amount and duration of direct sun exposure. If this was not possible, canopies erected over the material and shotcrete pump provided shade to aid in temperature control. Similar to the winter months, ACR used infrared and standard thermometers to verify the temperature of the substrate, water, pre-bagged material, and mixed material to ensure they stayed below the specified maximum temperatures. The


Fig. 6: *Shotcrete placement inside a heated bridge enclosure*

temperatures were also recorded on quality control checklists every hour.

The retaining walls posed an entirely different set of challenges. The walls ran the entire 2.67 miles (4.29 km) length of the trail between the bridges on both sides of the trail. Many of these walls were located in the backyards of residents and some of the houses were very close to the walls, at times separated only by a 4 to 5 ft (1.22 to 1.5 m) pathway. ACR had to coordinate with the general contractor and owner's engineers on a daily basis to ensure that the residents permitted ACR adequate access to their yards to perform the work. In addition, some of these homes maintained elaborate gardens and expensive landscaping, requiring specialized property protection.

Specifically, one of the yards ACR needed to access housed a picturesque koi pond and an herb garden owned by a well-known chef. This garden is closely tended by a professional gardener, and the harvest is used in several restaurants (Fig. 7). Thus, ACR had to deploy multiple levels of protection for the plants and planters from dust, debris, and overspray. Further, the retaining wall next to this garden was covered in decorative vines, and ACR had to coordinate with the chef's gardener to ensure proper pruning or removal without unnecessary damage to the surrounding foliage. In other areas, ACR had to install temporary framing on the outer edge coupled with protective mesh and tarps to ensure that the shotcrete work was not damaging homes and yards. ACR also encountered an area of retaining wall where the cap was directly above a residential balcony. To perform removals and shotcrete repairs without damaging property below, two stages of protection were deployed. First, ACR installed a fabric tarp along the guardrail of the trail to keep debris from travelling over the side. Additionally, the area designated for repair was framed to ensure that all chipping debris would remain on the trail-side instead of falling to the balcony and property below. This one-sided formwork also gave the nozzleman something to shoot against. As ACR progressed along this 2.67 mile (4.29 km) jobsite, encountering different temperaments of residents, gaining permission to access the repair areas along the retaining walls ran the spectrum of difficulty.

Significance to Project

When compared to form-and-place repair techniques, shotcrete proved a far more efficient method of repair on the 36 bridges and miles of retaining walls that allowed for quicker completion with excellent structural capability. As in all construction projects, time was of the essence. Many of the bridges required the erection of shoring towers simply to stabilize a severely

Fig. 7: Elaborate gardens of homeowners required covered repair areas that needed thorough planning, preparation, and coordination

deteriorated substructure and required them to be in place until the specified 14-day compressive strength tests of the shotcrete was met. The use of shotcrete and its versatility had many advantages over form-and-place. One advantage was the ability to remove the shoring towers long before the 14-day compressive strength requirement when the pre-bagged shotcrete material reached 70% of its strength. This allowed for reopening the streets in compliance with the City of Chicago's permit requirements. Another advantage in using shotcrete was repairing the retaining walls adjacent to private backyards, including that of a well-known chef. ACR staged the shotcrete equipment on the opposite side of the trail and ran the shotcrete hoses up and over the trail as opposed to through the yard and gardens. In addition, this set-up eliminated the need for tradesmen to access the yards to set-up and strip formwork for a form-and-place operation, thus completely preventing the damage or inconvenience that access could create. Using the shotcrete method also meant that there was no possibility of a form blowing out during casting and damaging the yard. The shotcrete process also allows a visual confirmation of encapsulation of the reinforcing bar throughout the shotcrete placement process, while cast-in-place work requires casting into a closed form where incomplete consolidation and resulting voids aren't evident until stripping the forms. After the shotcrete was placed, a double layer of curing compound was applied, thus eliminating the need to impede on private property for any form removal, grinding, or patching.

The scope of work resulted in over 15,000 ft^3 (425 m^3) of removal and replacement with high-quality shotcrete. All the shotcrete was placed by ACI-certified Nozzlemen employed by a qualified shotcrete contractor. The shotcrete was placed with a 0.42 water-cementitious materials ratio, along with the addition of 10% by weight of 3/8 in. (10 mm) river rock. Safety, time, and quality all significantly contributed to the very successful use of shotcrete by the Chicago Department of Transportation (CDOT) on "The 606" project. The general contractor and the subcontractor are also proud of their safety record of zero accident reports while working in one of the most congested parts of the city. All work was done to OSHA regulations and CDOT environmental requirements. All of the compressive strength test results exceeded the specification's requirement and the shotcrete solution resulted in a long-term, affordable repair with minimum impact on the surrounding community.

***Kevin Doyle** graduated from The Ohio State University in 2009 with a bachelor's degree in construction management. Having worked for a privately owned government contractor out of college, Doyle gained the experience from the owner's perspective that would prove valuable once he joined American Concrete Restorations, Inc., in April 2013. Doyle brought his understanding of the necessity for strong communication and teamwork between a contractor and owner to this project and helped to ensure project progress remained on track. "The 606"-Bloomingdale Trail is his first major project in which he helped manage, and thus Doyle is extremely proud that it has been awarded ASA's 2014 Outstanding Repair and Rehabilitation Project.*

The Outstanding Repair & Rehabilitation Project

Project Name
606-Bloomingdale Trail | Viaduct Repairs

Project Location
Chicago, IL

Shotcrete Contractor
American Concrete Restorations, Inc.*

General Contractor
Walsh Construction

Architect/Engineer
Transystems

Material Supplier/Manufacturer
SPEC MIX*, Putzmeister Shotcrete Technology*

Project Owner
City of Chicago—Department of Transportation

*Corporate Member of the
American Shotcrete Association

2014 Honorable Mention

Liberty Tunnel Arch Restoration with a Shotcrete Alternative

By Axel G. Nitschke and John Becker

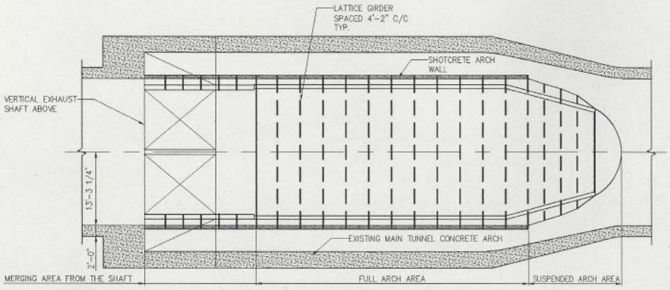


Fig. 1: Tunnel ventilation arch wall section plan view

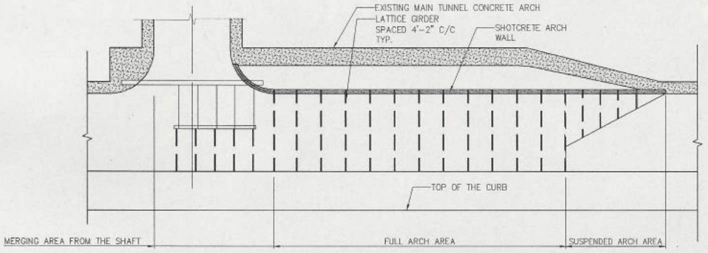


Fig. 2: Tunnel ventilation arch wall section—longitudinal section

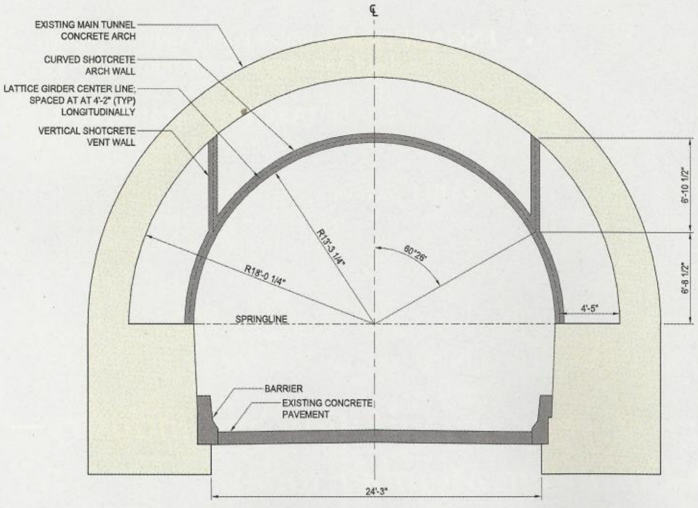


Fig. 3: Alternative design self-bearing shotcrete arch section

The Liberty Tunnel provides a direct commuting route from the South Hills suburbs to downtown Pittsburgh, PA. The Liberty Tunnel is a horseshoe-shaped tunnel consisting of two northbound and southbound tubes and has an overall length of 5888 ft (1795 m). The tunnel consists of two vertical vent shafts to draw exhaust from the midpoint of each tunnel and force a supply of fresh air into the tunnel through the so-called "arch walls." An arch wall is an arch structure which is offset from the structural lining of the tunnel to provide for air channels. The ventilation arch wall section acts like a macroscopic air nozzle—fresh air is supplied from the ventilation shaft and pushed along the vent supply area on either side of the arch wall. The arch walls are open at the end of the nozzle, which allows the fresh air to enter into the tunnel away from the exhaust point (Fig. 1 through 4).

Swank Construction Company was awarded the Liberty Tunnels rehabilitation project by the Pennsylvania Department of Transportation (PennDOT) in May 2013. The project included, among other scopes, the demolition and renewal of the ventilation arch walls inside the tunnels, close to the ventilation shaft. Gall Zeidler Consultants (GZ), in cooperation with Swank Construction and Coastal Gunite, provided an alternate design and construction concept for the Liberty Tunnels rehabilitation project.

Structurally, the arch wall section can be divided into three sections from left to right in Fig. 1 and 2: 1) merging area from the shaft; 2) full-arch area, where the arch wall is closed at the bottom; and 3) suspended arch area, where the arch wall is open at the bottom to provide an outlet for the fresh air (see also Fig. 4). This article focuses on the full-arch area (center) and does not address the merging area from the shaft (left) or the suspended arch area (right).

Arch Restoration

Original Design

The original arch wall used U-shaped steel profiles as structural members, which were tied with radial hangers to the structural tunnel arch above. Vertical walls separated the center part from the sidewall areas, as shown in Fig. 5. The original rehabilitation design proposed demolishing and renewing the existing ventilation arch walls, following the original design with U-shaped steel beams and radial hangers embedded in the concrete (refer to Fig. 5 and 6). The concrete arch was supposed to be reinforced with welded wire reinforcement. During the arch wall demolition, it was intended to use the existing steel framing hangers that were in good condition and replace the deteriorated ones. A curved steel formwork forming both sides of the free-standing arch wall was supposed to be used to form the cast-in-place arch. In addition, two vertical walls and concrete embedment of the hangers on top of the arch were to be formed and placed.

Self-consolidating concrete (SCC) is a high-performance concrete that can flow easily into tight and constricted spaces without segregating and without requiring vibration. However, fresh SCC exerts high hydrostatic stress, which has to be borne entirely by the formwork until the concrete develops strength. This creates the risk of rupturing the formwork and concrete blowouts. Therefore, specialized formwork consisting of steel or very strong timber formwork embedded with studs and anchors of sufficient strength is required to prevent concrete blowouts or lifting of the form from hydraulic stresses. Such custom-made formwork incurs high costs, especially due to its very limited reuse at the given application. In addition, the schedule impact by the risk of blowouts or deformation of the formwork was considered very high by the contractor, because the limited shutdown period of the tunnel left no time for on-site adjustments or rework.

Reusability of the existing hangers embedded in the concrete also posed an uncertainty because its usability could only be determined after the demolition of the existing arch wall. The number of deteriorated hangers or hangers which were damaged during the demolition was therefore unknown at the start of construction. Further, sorting out the hangers and replacing the deteriorated ones was considered a time-consuming activity in itself. The hangers also posed an additional hindrance during formwork installation.

Alternative Design

As an alternative design, the use of cast-in-place concrete was replaced by sprayed shotcrete and the structural system was modified into a self-bearing arch. The self-bearing arch allowed the complete removal of all hangers during the demolishing process.

The self-bearing shotcrete arch concept is often used to extend the underground section of a mined

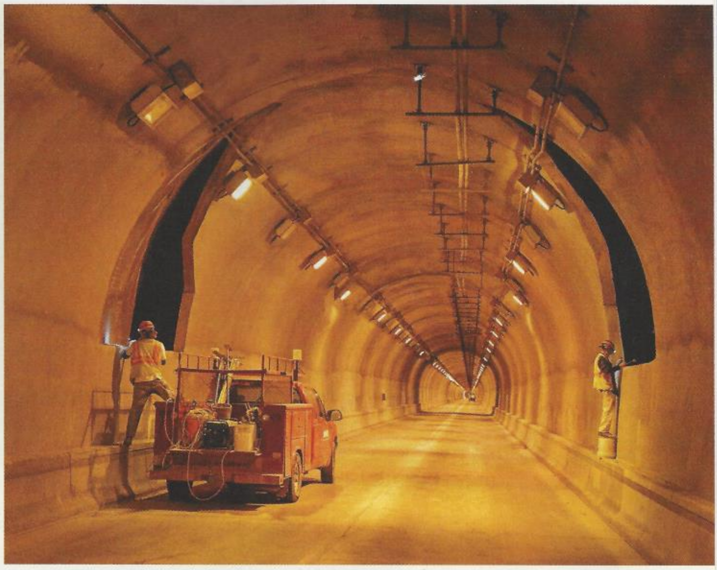


Fig. 4: Finished rehabilitation

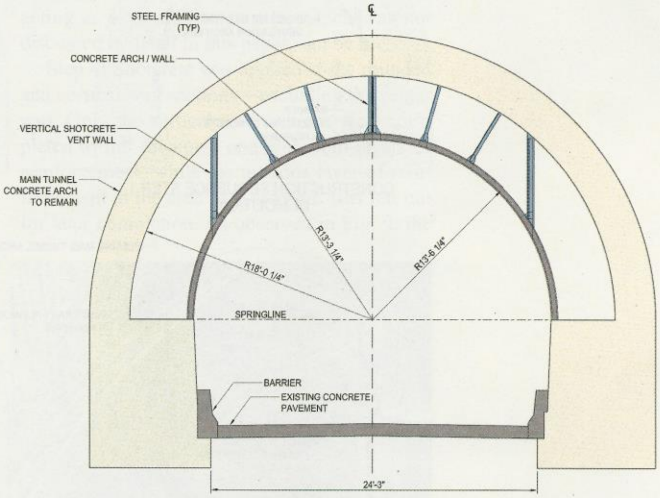


Fig. 5: Existing tunnel ventilation arch wall section—cross section

Fig. 6: Embedded hangers in existing void space between main tunnel and ventilation arch wall

tunnel into the open portal area by providing a free-standing arch often termed as shotcrete canopy. Recent examples for the use of shotcrete canopies can be found at the Weehawken Tunnel in New Jersey and Devil's Slide Tunnel in California. While the initial lining during tunnel excavation and support is applied against the ground, an artificial surface on the backside has to be provided for a free-standing arch to allow for the buildup of the shotcrete lining.

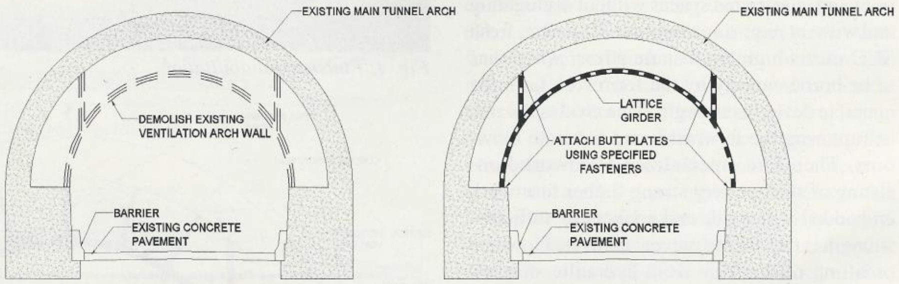
The cross section in Fig. 3 illustrates a typical configuration of a self-bearing shotcrete arch. Structurally, the arch wall is 6 in. (152 mm) thick and supports itself as a free-standing, self-bearing arch, loaded by the weight of the two vertical overlying walls. These vertical walls do not have any structural function and are for ventilation purposes only. The arch walls and the vertical walls have embedded lattice girders at a typical spacing of 4 ft-2 in. (1.27 m) center-to-center. The arches were reinforced with two layers of welded wire reinforcement, W9 x W9 at 6 in. (152 mm) center-to-center spacing in both directions, as a minimum reinforcement to control cracking from shrinkage and temperature changes.

Construction Sequence

The schematic of the construction sequence is illustrated in Fig. 7 and detailed in the following steps (see Fig. 4 and 7 through 10):

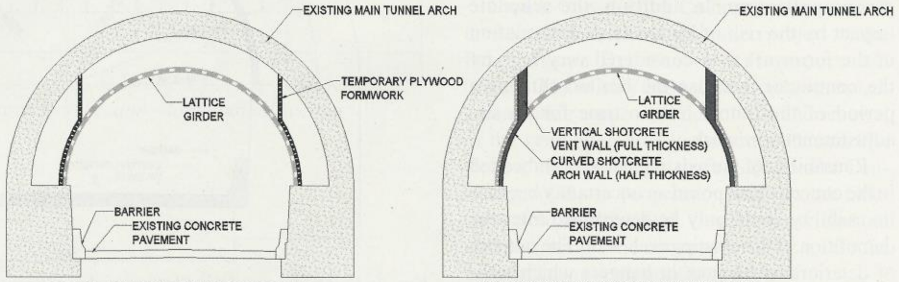
Step 1: The construction started with demolition of the existing ventilation arch wall.

Step 2: In the second step, lattice girders were installed along the arch periphery and along two vertical wall sections. The lattice girders were secured with undercut anchors at the top and dowels at the bottom of the arch of the main tunnel lining. The lattice girders were comprised of a



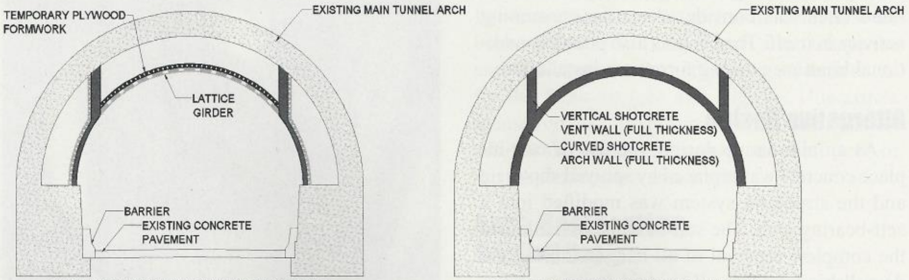
CONSTRUCTION SEQUENCE STEP 1
DEMOLITION

CONSTRUCTION SEQUENCE STEP 2
LATTICE GIRDER INSTALLATION



CONSTRUCTION SEQUENCE STEP 3
PREPARATION OF THE SIDE AND VERTICAL WALL

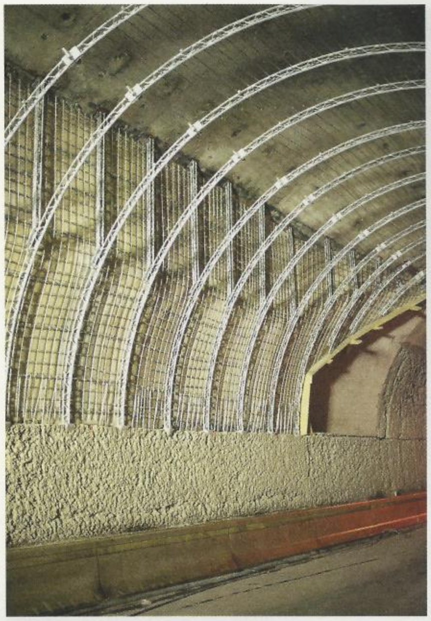
CONSTRUCTION SEQUENCE STEP 4
SHOTCRETE SIDE AND VERTICAL WALLS



CONSTRUCTION SEQUENCE STEP 5
PREPARATION OF THE CENTER ARCH

CONSTRUCTION SEQUENCE STEP 6
SHOTCRETE CENTER ARCH

Fig. 7: Typical construction sequence



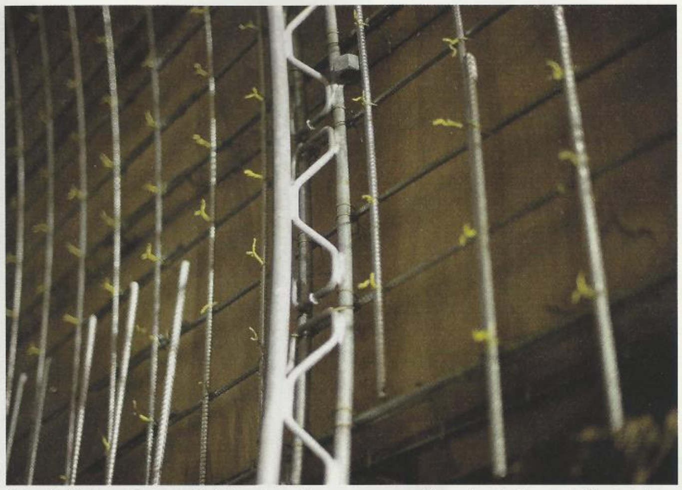


Fig. 8 (left and above): Construction sequence Step 3—lattice girder and extrados reinforcement sidewall sections

three-piece arch plus one piece each for each vertical ventilation wall on either side.

Step 3: A light plywood formwork was set up along with first layer of welded wire reinforcement at the extrados (exterior curve of the arch) side of the lattice girder. The center part of the arch was left open to provide access for the construction of the vertical walls. Figure 8 illustrates the erected lattice girders of the arch walls and vertical wall sections. The center arch section is open to allow shotcreting of the vertical walls. In the back, the suspended section of the arch wall, acting as a ventilation nozzle, which was not discussed in detail in this paper, can be seen.

Step 4: Shotcrete was applied at the rounded and vertical wall sections—excluding the center part. Only the vertical wall sections were completed to full thickness and with both layers of reinforcement, while the intrados layer of reinforcement at the arch wall sidewall was left out for later completion. As observed in Fig. 9, the

Fig. 9: Construction sequence Step 4—curved and vertical sidewall sections are shotcreted

Fig. 10: Construction sequence Step 5—preparation of center arch section

curved and vertical sidewall sections have been partially shotcreted.

Step 5: The center arch section was closed by installation of the plywood and reinforcement at the extrados side of the arch. As soon as the vertical wall sections were completed, the plywood and reinforcement in the center arch section could be installed and shotcreted, which is illustrated in Fig. 10. After this step, the intrados (interior curve of the arch) level of reinforcement covered by the final layer of trowel-finished shotcrete can be installed.

Step 6: The center arch section was sprayed up to the intrados layer of reinforcement, followed by the installation of the intrados layer of reinforcement along the entire arch and completion of the shotcrete arch wall to full thickness, including a trowel finish. Finally, at the end, the plywood at the backside was removed, completing the arch wall construction. Figure 4 shows the arch wall section after its rehabilitation, looking into the air nozzle opening. The smooth trowel finish of the shotcrete makes it difficult to recognize that shotcrete in lieu of cast-in-place concrete was used.

Construction Challenges

The shutdown period for tunnel closure was very limited and demanded a very tight and compact construction schedule. The construction was split into two phases: Phase 1 for the southbound tunnel and Phase 2 for the northbound tunnel. As part of the bid documents, PennDOT set forth 18-day closures per phase. Failure to meet the 18-day closure would result in a penalty of $40,000 per day. During the planning phase, it was apparent that meeting the 18-day restriction with the original design would be extremely challenging and alternatives were investigated. During development stages of the alternative shotcrete design, it was determined the arch walls could be completed in 16 days.

The demolition of the existing arch walls started immediately after tunnel closure, followed by the installation of new shotcrete arch walls. The southbound tunnel (Phase 1) was completed just hours before the opening of the tunnel for traffic. However, the northbound tunnel (Phase 2) was completed in about 14 days; 2 days under the maximum allowed 16 days.

The design specified stringent experience requirements for the shotcrete applicator to ensure the required high quality. Coastal Gunite was the subcontracted shotcrete specialist contractor and worked with a crew of nine to 12 people per 12-hour shift. The concrete material was hauled in dry bulk sacks and mixed on site inside a concrete truck inside the tunnel, which ensured sufficient quantities available in place given the tight construction schedule. The concrete mixture included polyfibers and a corrosion inhibitor. Excluding the finish coat, the wet-mix shotcrete used a liquid accelerator, injected at the shotcrete nozzle, to reach the specified set times and meet the early strength requirements required by the design. The shotcrete was placed in three lifts per wall. The first layer of shotcrete was placed encapsulating the first layer of mesh and left enough of the lattice girder exposed such that the second layer could be installed. The second placement encapsulated all of the steel and was left rough so that a monolithic finish coat could be applied last to provide aesthetic appeal. The final layer was finished with a broom and was sprayed with a curing compound to attain proper cure and avoid surface cracking.

Conclusions

For the Liberty Tunnel rehabilitation project, time was of the essence due to a short and limited closure of the tunnel. The alternative design of the self-bearing shotcrete ventilation arch wall provided the contractor greater flexibility and reduced construction risk during the ventilation arch wall installation.

The simplicity in the design and the easy and quick installation of the shotcrete arch wall system allowed the project to be completed on time and within budget. The tunnel was even completed 2 days earlier than the proposed schedule and on budget with 18% cost savings to the owner. Such design has showcased the effective and fast use of shotcrete as means for rehabilitation and repair works in existing tunnels that only allow limited time for tunnel closures.

Honorable Mention

Project Name
Liberty Tunnel Arch Restoration

Project Location
Pittsburgh, PA

Shotcrete Contractor
Coastal Gunite Construction Company*

General Contractor
Swank Construction Company, LLC

Architect/Engineer
Gall Zeidler Consultants

Project Consultant/Inspection
Hill International Inc.

Material Supplier/Manufacturer
The QUIKRETE Companies*

Project Owner
Pennsylvania Department of Transportation

*Corporate Member of the
American Shotcrete Association

References

FHWA-NHI-09-010, 2009, "Technical Manual for Design and Construction of Road Tunnels —Civil Element," Federal Highway Administration, Washington, DC, 704 pp.

ACI Committee 318, 2005, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary," American Concrete Institute, Farmington Hills, MI, 430 pp.

***Axel G. Nitschke** received his MSc and PhD in civil engineering in 1993 and 1998, respectively, from Ruhr University Bochum, Bochum, Germany, and is a licensed professional engineer in Virginia and California. He has gained more than 20 years of in-depth, on-the-job experience in all aspects of underground construction, geotechnical engineering, and mining. He has worked on the engineering and construction of a large number of tunnel projects in Europe, the United States, Canada, and Colombia. He is well-experienced in all ground conditions, ranging from soft ground to hard rock, and the associated implications for design and construction methods. Nitschke has held key positions such as Senior NATM Engineer, Contract/Claims Manager, Risk Manager, Design Manager, and Project Manager.*

***John Becker** is an ACI Certified Nozzleman who, for the last 5 years, has worked in many capacities—most recently as Project Manager—for Coastal Gunite Construction Company, based in Cambridge, MD. In addition to the Fort McHenry Tunnel, he has been involved with many shotcrete projects large and small, including the $15 million Bonner Bridge Rehabilitation Project in Nags Head, NC, and the $5 million Old Mill Creek Sewer Rehabilitation Project in St. Louis, MO.*