Dr. G. Sauer Corporation, all

PUSHING BACK

Seven deformed flood control tunnels that pass through a rail embankment were enlarged using a one-of-a-kind expander that pushed the deformed liner plates back into position with minimal disruption to rail traffic. **By Brian Fortner**

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Construction crews had to build a cofferdam around transit piers near the downstream opening of the tunnels, opposite top. *The expanding device,* opposite below left, *was driven into the tunnels. Shoes on each leg straddled the steel sets, and hydraulic jacks pushed them against the deformed liner plate. Timber pile bracing placed in 1994 kept the deformations—some as much as 1.25 ft (0.4 m) near the crown of the tunnels—from increasing, but they also reduced flow capacity and could be knocked loose by debris,* opposite below right. *The seven tunnels carry normal flows, but a concrete arch and a public bike path will help convey water from a 100-year flood,* right.

Cameron Run flows into the Potomac River in Alexandria, Virginia, just south of Washington, D.C. This unremarkable urban stream primarily carries runoff and serves as a flood control channel. In 1975 the city built seven parallel 20 ft (6 m) diameter tunnels to convey the stream through an earthen rail embankment, but after 20 years sections of the corrugated steel liner plate had deformed as much as 1.25 ft (0.4 m) on each side of the crown in six of the seven tunnels.

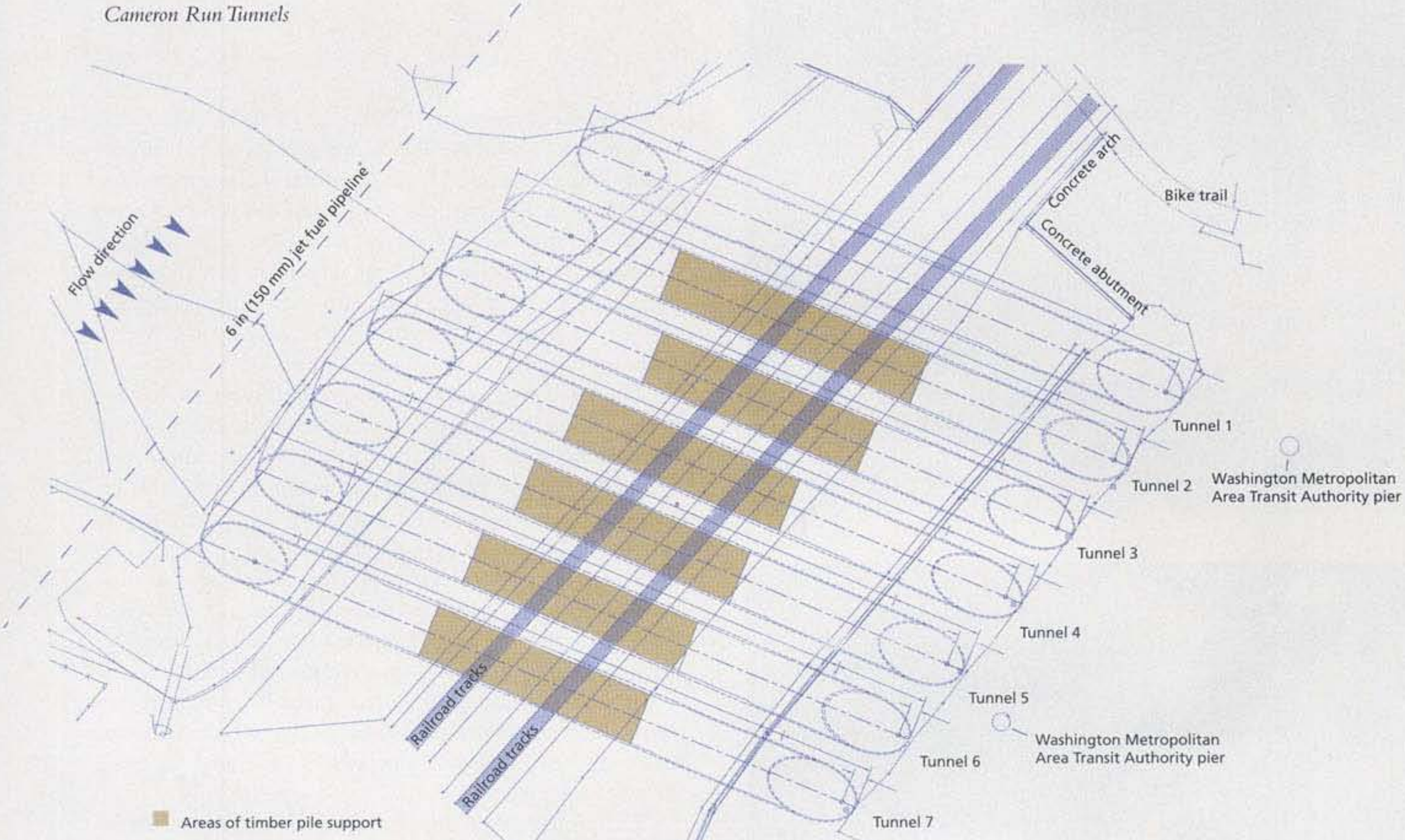
City engineers installed temporary wooden pile bracing in the tunnels in 1994 hoping to halt the deformations until a permanent solution could be developed. In the meantime, the hydraulic capacity of the tunnels had decreased because of the deformations and the installation of the bracing, which trapped debris inside the tunnels. In addition, the timber piles were subjected to periodic high-water flows, which could carry debris large enough to dislodge the bracing and threaten the stability of the tunnels.

In 1999 the city hired the Dr. G. Sauer Corporation, of Herndon, Virginia, to provide design and construction management services for the rehabilitation of the Cameron Run tunnels. One of the requirements that the city imposed on the project was that it have minimal impact on a popular public bike path along Cameron Run and on a pair of CSX rail tracks located less than 30 ft (9 m) above the tunnels. The tracks carry more than 45 freight and passenger trains through the area each day, and the tunnel repair scheme could not significantly alter rail operations.

The project also had to address the point loading on the tunnels—which was thought to be causing the tunnel liners to buckle—and the effect of any rehabilitation scheme on the hydraulic flow capacity. "These two requirements led to the adoption of our design," says Vojtech Gall, a vice president of the Dr. G. Sauer Corporation, "which would expand the existing lining, provide immediate steel support, and then provide permanent shotcrete lining to ensure the tunnel shape."

The design for the $3.5-million Cameron Run tunnel rehabilitation project involved a tricky and relatively unproven method of pushing the liner plates back into position and was not without its doubters. According to Gall, some prequalified construction companies vying for the project criticized the design because their experiences with pushing deformed tunnel liner plates had not been encouraging. Those projects involved new tunnel construction and undisturbed soil. The liner plates, when pushed, distributed the loads to large areas and often the liners could not be moved, he says.

The Cameron Run project, on the other hand, involved a fill embankment thought to contain voids behind the liner plate, a nonrigid tunnel liner, and point-load deformations. "We planned to meet a point load with a new point load in a very flexible lining condition with loosely compacted soil behind the lining," Gall says.



Tunnel length: 158 to 175 ft (48 to 53 m)
Tunnel diameter: approximately 20 ft (6 m)
Tunnel crown elevation: approximately 50 ft (15 m)
Railroad track elevation: approximately 82 ft (25 m)

Before awarding the project contracts, the city considered many rehabilitation alternatives, including slipping a liner inside the tunnels or lining the deformed tunnels with structural shotcrete. These methods, however, would have decreased flow capacity, been too costly, or not have addressed the loading problem that caused the deformations in the first place. "Simple shotcrete would provide an irregular surface and would not address what was going on in the embankment," says Lucky Stokes, the division chief of construction and inspection services for the city of Alexandria. Instead, city engineers wanted to repair the deformations to more evenly distribute the loads that were causing the liner plate to buckle.

The soil above the spring line is considered to be loosely compacted silty sandy material, and over time the tunnels could experience additional deformation, Gall says. Pushing back on the point loads and redistributing them around the entire liner would mitigate the deformation.

At first the city was a bit surprised by the proposal, says Mohamed Halim, the engineering and design division chief for the city of Alexandria. "We never thought about pushing back," he says.

Geotechnical assessments of the site included boring from the top of the embankment to below the invert level at three locations, as well as conducting probe drills along the crown of the tunnels to determine the condition of the liner plate and the geotechnical conditions behind it. The engineering assessment indicated that preliminary investigations, which revealed voids in the embankment, were correct. Surveys inside the tunnels also mapped the deformation contours so that profiles could be developed for each section. The city awarded a construction contract to Merco, Inc., based in Lebanon, New Jersey, and construction began in February 2000.

The Cameron Run tunnels range in length from 158 to 175 ft (48 to 53 m) at the crown. The deformations occurred primarily in the center sections of the tunnels, which is where the timber pile bracing was placed and the majority of the structural reinforcement was installed (see illustration). The center sections of the tunnels are also subjected to the most overburden.

The project site had many obstacles: the bike path, the two rail tracks, two Washington Metropolitan Area Transit Authority piers less than 25 ft (7.6 m) from the downstream opening

Once the liner plate was expanded, short filler pieces in the steel sets were replaced with longer sections to match the new tunnel profile. About 120 ft (37 m) in each tunnel was lined with steel sets spaced 3 ft (0.9 m) apart, top. *The finished tunnel profile includes a concrete invert,* above. *The steel sets and shotcrete layers are 6.25 in. (160 mm) deep, which left the inner flange of the steel set exposed in the tunnels.*

of the tunnels, and a 6 in. (150 mm) jet fuel pipeline that leads to the Ronald Reagan Washington National Airport and is located about 25 ft (7.6 m) from the upstream tunnel openings. The pipeline was buried about 6 ft (1.8 m) below the stream channel, and construction crews were restricted from driving over it when the area was wet, according to Kurt Egger, the construction manager for the Dr. G. Sauer Corporation. "The goal for the Metro piers was simply not to hit them," he says.

The engineered rehabilitation system relied on a carefully orchestrated construction sequence. Because the tunnels are so close together—separated by about 8 ft (2.4 m) at the spring line and by about 28 ft (8.5 m) on center—each relies on the others for support. "If one would go they all would go," Stokes says.

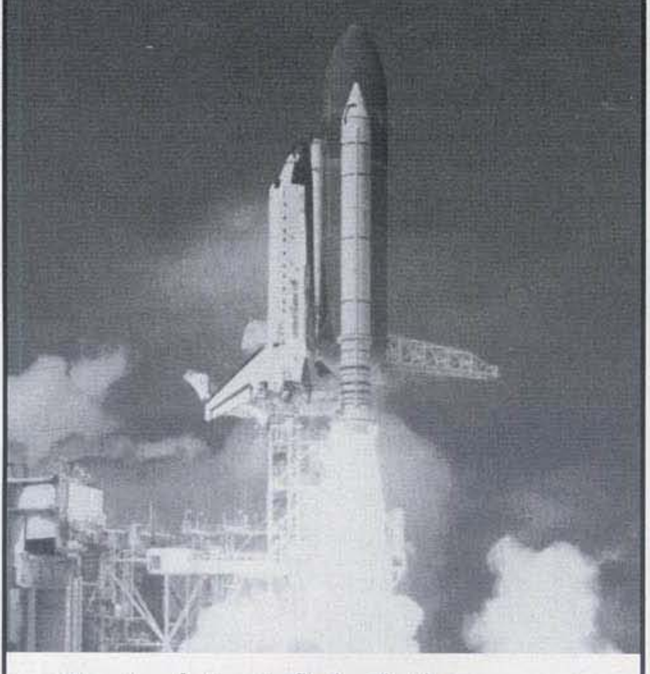
The project was divided into two phases so that tunnels 1 through 4 were rehabilitated first, and tunnels 5 through 7 would carry Cameron Run water flow. The water diversion structure was then moved so that tunnels 5 through 7 could be repaired. Tunnel 4 was kept dry throughout the entire project, serving as a seam between the two phases. Rehabilitation work in tunnel 4 occurred during both phases.

The project relied on shoring the tunnels with circular steel sets fitted to the tunnel profile so that the timber piles could be removed. Construction crews proceeded in 10 ft (3 m) increments inside the tunnels, removing timber piles and placing circular steel sets every 3 ft (0.9 m). "We assumed the timbers were load carrying and we needed a certain sequence to replace them with an engineered system," Gall says.

Tunnel 1, which was closest to the bike path and a concrete arch bridge that carried the bike path under the rail tracks, was the only tunnel that did not experience significant buckling and therefore did not include timber pile bracing. Even so, the liner plate in this tunnel had deteriorated in spots and about 50 permanent steel sets were placed in the tunnel. Then the entire length was lined with shotcrete. Tunnel 2 had the most severe deformations.

The construction sequence required the construction crews to install steel sets in adjacent tunnels before expanding any tunnel so that the stresses would be distributed to neighboring tunnels. Each tunnel had to be expanded before the shotcrete in adjacent tunnels had reached its 28-day strength or, in some cases, been applied. "We were concerned that the shotcrete lining could crack should any forces be shed from adjacent tunnels," Gall says.

The steel ribs consist of 6.25 in. (160 mm) deep I beams in a circular shape. Short filler pieces were used to match the tunnel profile initially. Once the liner plates



were expanded, the short filler pieces were replaced with longer sections to match the new tunnel profile. Each tunnel contains about 40 permanent steel sets over a distance of 120 ft (37 m). Temporary steel sets—three at each end of the expansion area—were installed for support.

A liner plate expander was used to shove the deformed sections back into alignment or to positions near their original alignment. The expander did not push any liner plates more than 1 ft (0.3 m). "We were not required to get rid of the deformations completely," Gall says, "but only to adjust them to the minimum geometry required for the hydraulic throughput."

The goal was to maintain a minimum 18 ft (5.5 m) diameter tunnel for hydraulic flow, which would be needed for the 100-year, 40,000 cfs (1,130 m^3/s) flood. Each tunnel must convey 4,000 cfs (113 m^3/s); the remaining 12,000 cfs (340 m^3/s) would flood the bike path and be conveyed under the railway's concrete arch bridge on one end of the embankment.

Because the corrugated liner plate would be covered with a smooth shotcrete surface, the flow characteristics would be improved and the diameter of the tunnels could thus be made smaller. Some tunnels are not circular but are 17.5 ft (5.3 m) wide and 18.75 ft (5.7 m) high to compensate for lost hydraulics, Egger says. For example, construction crews ran into grout and consolidated soil behind the liner plates in the last tunnel—tunnel 7. "We quickly saw the limit of the method," Egger says.

"Because the deformation was not uniform, knowing how much and where to push was very difficult," Halim says. In some cases, the construction crews could push on both sides of a tunnel at one time. Many decisions as to how much and when to work the hydraulic jacks were made in the field after observing the liner's behavior. In only two cases did the corrugated liner rip, necessitating the welding of steel plates. "Overall it was a very controlled process," Gall says.

The deformations typically occurred between the 9 and 11 o'clock positions and the 1 and 3 o'clock positions in the tunnels, so the expander was designed to be adjustable. The expander was attached to a steel set and placed against the invert of the tunnel, which had been reinforced. Crews then activated the 200 ton (183 Mg) hydraulic jacks on each leg to push against the deformed liner plate. Once the liner plate reached a predetermined position close to its original profile, the short filler piece was replaced with a longer, permanent steel piece that more accurately fit the new tunnel profile. The expander was then moved to the next steel set. Gall describes the process as an "expansion front that moved down the tunnels."

Once the tunnels were lined with steel sets and expanded, structural shotcrete reinforced with steel fibers was applied for additional support. A final shotcrete layer without fibers provided the smooth surface that would augment hydraulic capacity. The structural shotcrete is 5.25 in. (13 mm) thick and the finish layer is 1 in. (25 mm).

The design and construction team worked closely with rail officials from CSX, which owns the tracks above the tunnels. A detailed instrumentation scheme measured strain and tunnel roof leveling points. The measurements depicted how the tunnels were reacting to the new expansion and support procedure. A second set of instruments included settlement markers for the railroad tracks. Subsurface settlement markers about 4 ft (1.2 m) deep in the soil measured subsurface soil behavior under the track.

The rail officials required that settlements not exceed 1 in. (25 mm). This occurred only once, and CSX sent a crew to backfill the affected areas with ballast and level the tracks—a routine chore for most rail companies. The ground underwent a secondary compaction in response to the restructuring of the soil behind the linings, which led to surface settlement at track level, Gall says.

The only major problem during construction was high water flows. On at least three occasions the cofferdam, which was originally a berm, was overtopped with floodwater. The first incident washed away the berm, so the construction crew then built crib walls. Two more floods after heavy rains in the summer of 2000 overtopped the cofferdam, but crews had enough time to shore up the tunnel work. The cofferdam could not exceed an elevation of 38 ft (11.5 m) above sea level, or 6 ft (1.8 m) above ground level, because city officials did not want the bike path, at an elevation of 39 ft (12 m), to be flooded during heavy rains, according to Egger.

More than 750 ft (230 m) of tunnel underwent expansion and more than 190 tons (172 Mg) of steel was used in the project. Construction was completed in May of this year after the contractor installed concrete aprons and used shotcrete to line the embankment around the tunnels to improve the flow characteristics. Although the Cameron Run tunnel rehabilitation project was fairly small—in both size and cost—the geotechnical work involved in the design and construction can be considered groundbreaking.

"Anybody can go in and design some conservative long-term support, whether it be shotcrete, steel sets, cast-in-place concrete, or a steel tube with grout behind it," Gall says. "The most interesting thing about this project is that we enlarged the tunnel to meet flow requirements and optimized the support by taking away the point loads," he says. "And we did all this under an operating railroad." ■