

## FEATURE ARTICLE

# Modeling helps tame surges in rapidly filling storage tunnels

Deep tunnels have been used for decades for the temporary storage of large volumes of urban runoff, both storm water and combined sewer overflow (CSO). Tunnels are attractive because they reduce surface disruption and do double duty as storage and conveyance systems, collecting overflows from multiple locations and transporting them for treatment to various facilities. Like any hydraulic system, however, there are dynamic effects that must be fully understood during the design phase so that the final constructed product does not have unintended negative consequences. Preliminary sizing of storage tunnels is typically based on the total volume required. For example, if studies have determined that a volume of 56.8 ML (15 million gal) will provide the intended level of control, then that figure can be used, along with a preliminary idea of the desired tunnel length, to compute the required diameter. Of course, filling a long tube with water from various points along the way is not at all the same as pouring water into a bucket, and these dynamic effects require additional attention from design engineers.

The rapid filling of storage tunnels can lead to the formation of bores, which are essentially moving walls of water. An open channel bore can build in height until it reaches the crown of the tunnel, at which point it becomes a pipe-filling bore. Figure 1 depicts both kinds of bores moving upwards in a rapidly filling tunnel. Bores can strike the ends of tunnels with tremendous force, driving water and entrained air upwards into dropshafts and creating strong pressure surges in portions of the tunnel that are already filled. If the hydraulic surges are high enough to reach grade, they can cause overflows and/or damage structures at the surface.

Trapped air pockets can occur through several phenomena, including the reflection of bores off dropshaft structures and the occurrence of “premature pressurization.” The latter refers to the situation where the inflow to a tunnel is increasing more rapidly than the tunnel can convey it, such that the pipe becomes surcharged at an upstream point while points downstream are still flowing as an open channel. These air pockets are a great nuisance as they migrate toward points in the tunnel where they can rise to the surface, which are often shafts that are already filled with water (Fig. 2). The “geysers” that results can be hazardous and costly.

### Modeling approaches

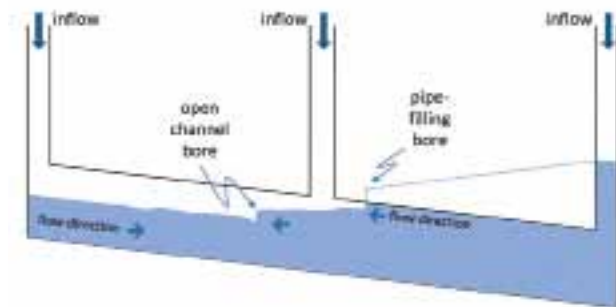
The standard approach to hydraulic modeling of waste water and stormwater collection systems has evolved considerably in the last decade, to where sophisticated and powerful models can easily be built on

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**FIG. 1**

**Schematic depiction of bores in rapidly filling tunnels .**



a typical desktop computer. These models employ a “link-node” framework, in which (in the simplest of terms) the sewer pipes are the “links” and the manholes are the “nodes.” A model simulation will produce a time history of flow in each link and water depth at each node. While these models are capable of realistically simulating a variety of real-world flow characteristics in sewer systems, including backwater effects, reversals, surcharging and even surface flooding, the link-node framework is unable to accurately simulate the issues associated with rapid filling for a number of reasons. The main issue is that the flow in a link is required to be constant from one end to the other. In rapid filling, however, there are dramatic differences in flow and depth occurring over relatively short distances. Further, link-node models represent pressure flow in a simplified way that neglects the compressibility of water and, thus, will not simulate pressure waves that arise from the sudden reversal of flow that occurs when a bore strikes a dropshaft. Lastly, link-node models handle the transition from gravity flow to pressure flow in an approximate fashion that is functional, but will not simulate subatmospheric pressures that result from surge waves.

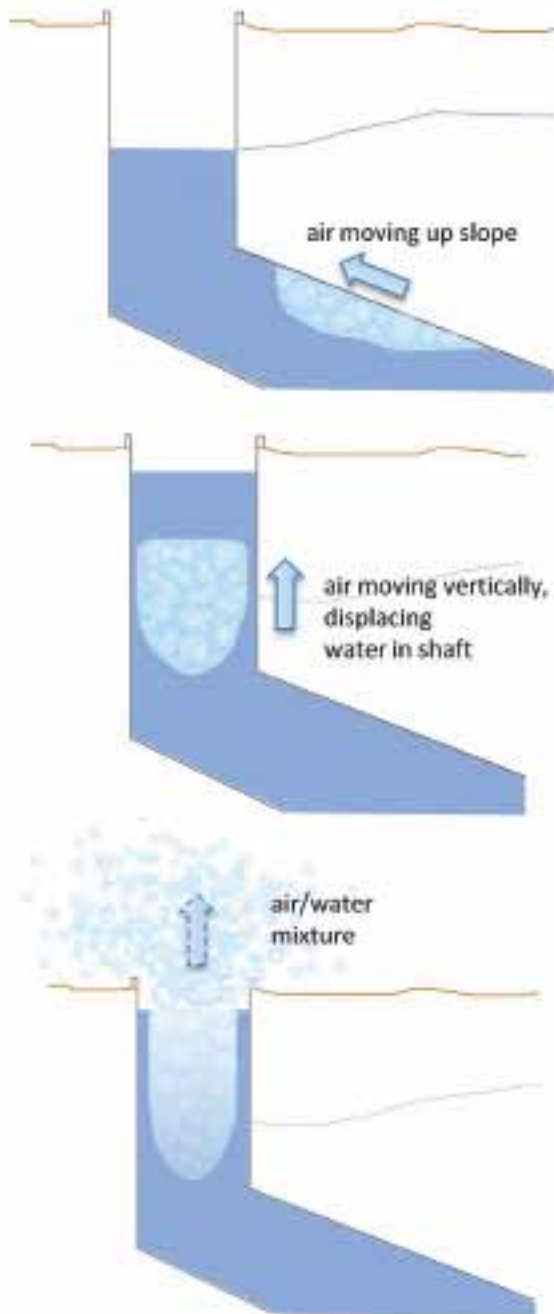
A model for simulating surges in tunnels needs to overcome all of these limitations. The problem has been attacked from different angles by various researchers over the years, and there are adequate models available for certain limiting cases, such as a single pipe-filling bore. Hydraulic transients in fully pressurized systems can be simulated by an approach known as the method of characteristics (MOC), which has a long history of successful application to waterhammer analysis for pressurized water distribution systems. Although MOC alone will not handle the rapid filling problem, there is an approach known as “shock fitting” in which a pipe-filling bore is assumed to occur, and the movement of the bore is tracked through the conservation of mass, with MOC employed to calculate the surge effects. This approach has been used with some success. But the assumption of the pipe-

filling bore must be robust, and that is not always the case. A different approach, known as “shock capturing,” employs a numerical method to predict the actual of formation of bores, which may or may not reach the crown of the pipe, and then track their movement.

Recent research at the University of Michigan by Vasconcelos and Wright (all citations) has produced a refined shock capturing model and validated it against extensive

**FIG. 2**

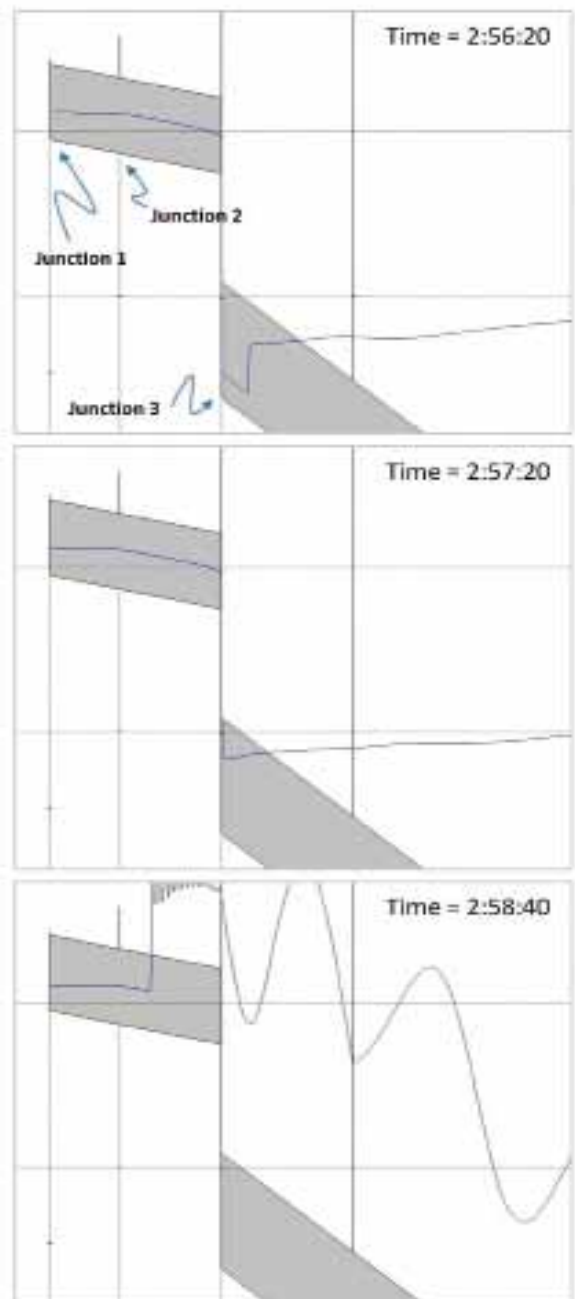
**Schematic depiction of air pocket movement.**



laboratory-scale physical hydraulic models. This more generalized model handles multiple bores, any of which can transition from open channel to pipe-filling and back again, as well as pressure waves resulting from reflection-induced flow reversals. The model also uses the novel approach of conceptually separating hydrostatic pressure, representing water depth in the tunnel, from the surcharge pressures that occur only in pressurized conditions. This idea, in

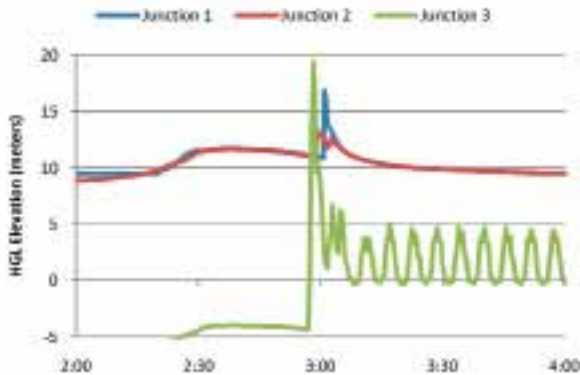
**FIG. 3**

**Effects of bore reflection in drop structure.**



**FIG. 4**

**Time series of HGLs corresponding to Fig. 3.**



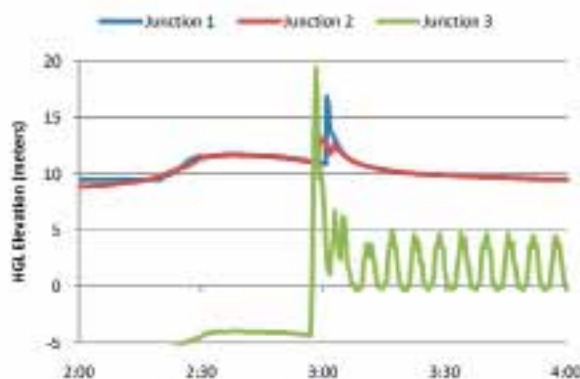
conjunction with the structural equivalence between unsteady incompressible flow equations in elastic pipes and unsteady open channel flow equations, allows the model to simulate both flow regimes using the same generalized set of equations, and readily model the transition from open channel flow to closed conduit flow. The model framework is documented in peer-reviewed publications. LimnoTech, in conjunction with University of Michigan scholars, has developed an implementation of the model called surge and hydraulic analysis for tunnels (SHAFT). The SHAFT model has been successfully applied to CSO storage tunnels that are currently under design in Washington, D.C. and London, England, with other applications to follow. SHAFT helped identify potential surge issues in both tunnel systems and was used to evaluate design changes to reduce the impact of surges.

### Applications

SHAFT has been applied to several large combined sewer tunnel storage projects that are currently under design; two project owners discussed in this article are the District of Columbia Water and Sewer Authority (DCWASA) in Washington D.C., and Thames Water (TW) in London,

**FIG. 5**

**Effect of steep tunnel slope on bore propagation.**



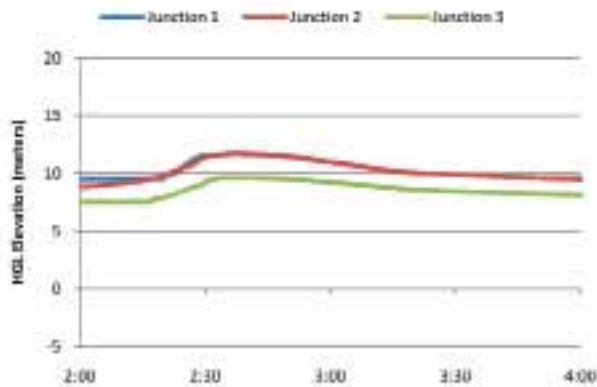
England. The model's flexibility was put to the test in these early stages when ongoing subsurface exploration can lead to frequent changes in alignment and geometry. SHAFT could identify general surge issues arising from a variety of tunnel configurations and, as the alignments became finalized, the model was also used to examine details such as venting and offline storage locations.

### District of Columbia

The DCWASA long-term control plan (2002) includes a range of controls that are designed to capture, on average, more than 7.6 GL/a (2 billion gal/year) of CSO that would otherwise overflow to receiving waters that include the Potomac and Anacostia rivers and Rock Creek. The centerpiece of the controls is a system of three tunnels that, when completed, will stretch nearly 17 km (10.5 miles) and provide more than 719 ML (190 million gal) of storage. The Anacostia River Tunnel (ART) will follow a route near the river and collect CSO from several outfalls along the way. At Poplar Point, it will connect to the Blue Plains Tunnel (BPT), which will convey the wastewater the rest of the way to the Blue Plains Wastewater Treatment Plant on the Potomac River. The ART and BPT will be constructed in the first phase and, together, will consist of nearly 11 km (7 miles) of 7-m- (23-ft-) diameter tunnel at depths ranging from 25 to 36 m (82 to 118 ft) below grade. The Northeast Boundary Tunnel (NEBT) will be built in a second phase, adding another 4.6 km (2.8 miles) of 7-m (23-ft-) diameter tunnel, along with 4.7 km (2.8 miles) of 4.6-m- (15-ft-) diameter tunnel and nearly 4 km (2.5 miles) of 3.7-m- (12-ft-) diameter tunnel.

SHAFT was used to simulate a large number of different tunnel configurations during the preliminary design process. The conditions simulated could be varied in three essentially independent ways: tunnel layout/geometry, filling scenario and river surface elevation. The different layouts were provided by the tunnel design team, whereas the different filling scenarios came from a link-node model of the DCWASA collection system that was subjected to different rainfall events. Some filling scenarios began with an empty tunnel and others with the tunnel partially full to simulate back-to-back events. Lastly, different water surface elevations in the Potomac and Anacostia rivers simulated the effects of unusually high tides on the outflow characteristics of the tunnel.

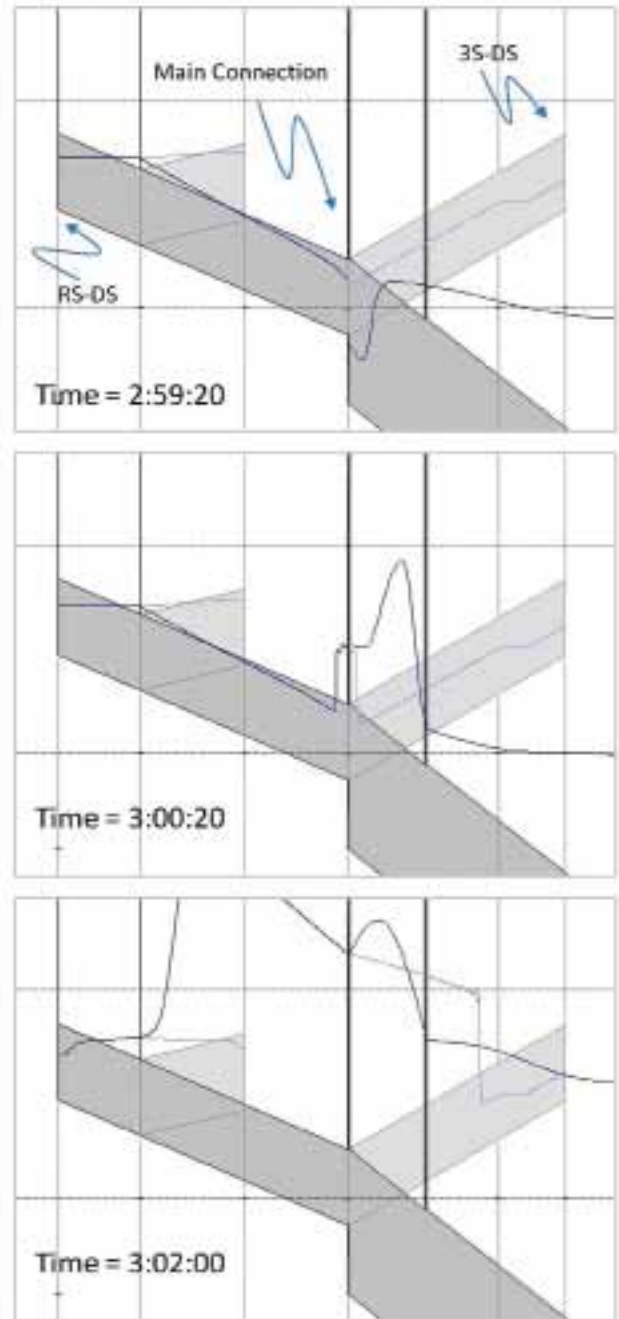
Simulations focused on two different storm events — the 15-year, six-hour storm and the 100-year, six-hour storm. The 15-year storm was of interest because of a requirement to control flooding in the northeast boundary area up to this particular level. The 100-year storm represented a sort of worst-case scenario, motivated by the idea that the storage tunnels should “do no harm.” While the system will clearly overflow in this case, it is still important to prevent surge-related damage to structures, geysers due to the presence of air pockets and the like. Not surprisingly, the 100-year storm produced the most dramatic surge-related effects, which led to several design modifications intended to mitigate them.

**FIG. 6****Time series of HGLs corresponding to Fig. 5.**

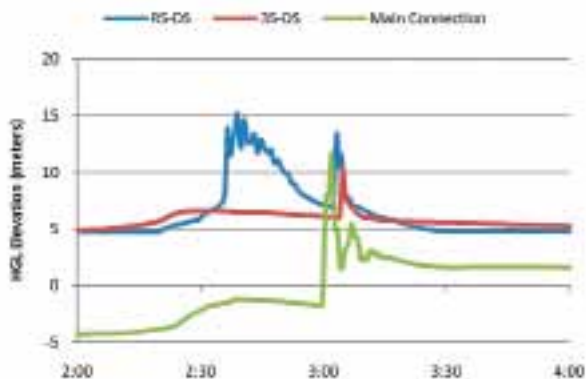
An early alignment had a portion of the NEBT at a slope of 0.46 percent, leading to a shaft with a 13.6-m (44.6-ft) vertical drop. Upstream of this drop shaft the tunnel diameter is reduced to 4.6 m (15-ft). SHAFT simulations using the 100-year storm showed a large open channel bore striking this shaft and resulting in a large spike in HGL. Figure 3 shows three snapshots of the water surface elevation in the tunnel, and Fig. 4 shows a time series of the HGL at the drop shaft and two other shafts at upstream locations. In the first panel of Fig. 3 (in which the vertical scale is exaggerated), the bore is closing in on the drop shaft. In the second panel, 60 seconds later, the bore has reflected and an air pocket is trapped. In the final panel, there is now a pipe-filling bore in the smaller-diameter tunnel, along with large oscillations in pressure in the main tunnel.

Ongoing geotechnical investigations suggested that a steeper slope had advantages in terms of constructability and SHAFT demonstrated that this configuration had advantages in terms of surge control as well. Figure 5 shows the alternate arrangement, in which the 7-m- (23-ft-) diameter tunnel is at a slope of 0.83 percent and meets the smaller diameter portion of the tunnel invert-to-invert. The three panels, representing the same moments of the scenario as shown in Fig. 3, show how the steeper slope has taken a great deal of momentum out of the bore, such that it fails to strike the shaft; no air pocket is formed, either. Figure 6 shows that the HGLs no longer have the spikes associated with surge propagation. While it is important to note that constructability was the chief driver behind this design change, SHAFT demonstrated that the steeper slope had other advantages as well.

The next results shown here are from a later stage in the design, in which the same location of the NEBT has now become a three-way junction with multiple smaller-diameter branches. An economic analysis suggested that the upper branches could have a diameter of 3.7 m (12 ft), instead of the original diameter of 4.6 m (15 ft), and that the tunnels would just surcharge at the design inflow rates for the 100-year storm. While this approach is often acceptable, SHAFT was used to investigate whether the surcharge

**FIG. 7****Propagation of bores in surcharged tunnel.**

condition would pose surge-related difficulties. Figures 7 and 8 illustrate the story. Other changes to system volume and inflow rates meant that the bore now completely reaches this location and it is seen that pipe-filling bores are created in the branch tunnels. The HGLs in Fig. 8 show the effect of the bore initially striking the upstream end (RS-DS), as well as the later impact at 3S-DS and the resulting reflections. Note that peak HGLs at all of these locations exceed 10 m

**FIG. 8****Time series of HGLs corresponding to Fig. 7.**

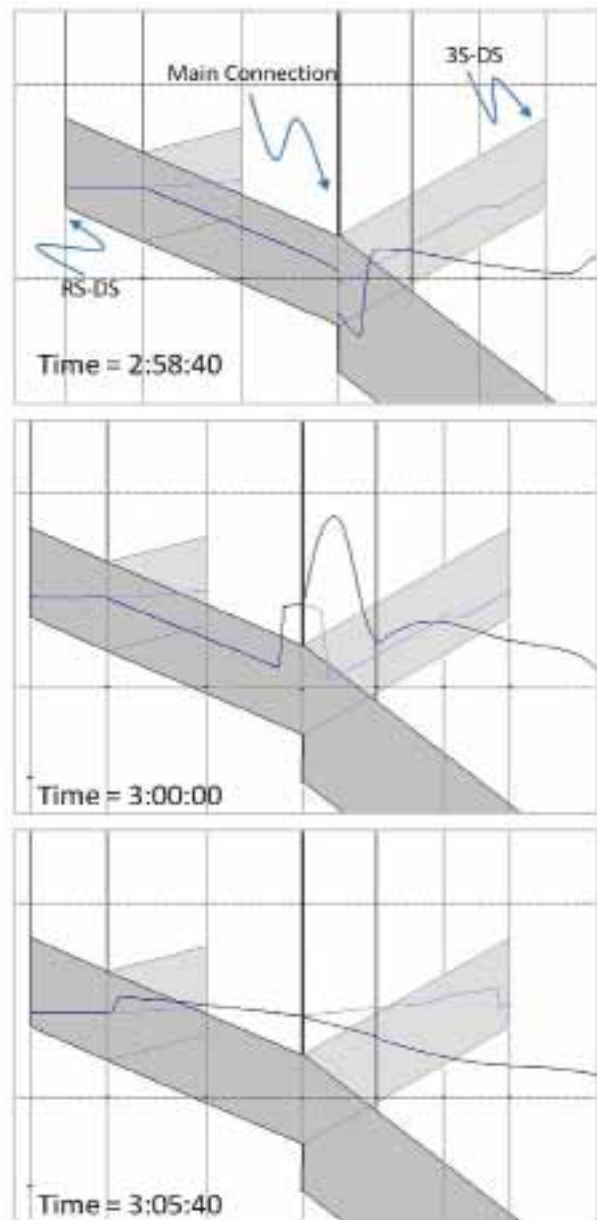
(33 ft), which is well above grade and would lead to surface flooding and/or structure damage.

Restoring the branch tunnels to their original diameter of 4.6 m (15 ft) not only provides additional storage volume but also changes the effect of the bore propagation in the most upstream reaches. SHAFT results for this configuration are shown in Figs. 9 and 10. The pipe-filling bore in the large tunnel translates into two such bores in the branches (second panel). But the additional volume in the branches allows these bores to transition to open channel bores and they eventually run themselves down before causing excessive surge pressures. As Fig. 10 indicates, there are moderate spikes at the upstream ends of the branches but peak HGLs barely reach 6 m (20 ft), which is below the critical elevation at these locations. Incidentally, this simulation is a good example of how a shock capturing model can simulate the formation and degradation of bores, as opposed to the shock fitting models that assume a pipe filling bore is present continually.

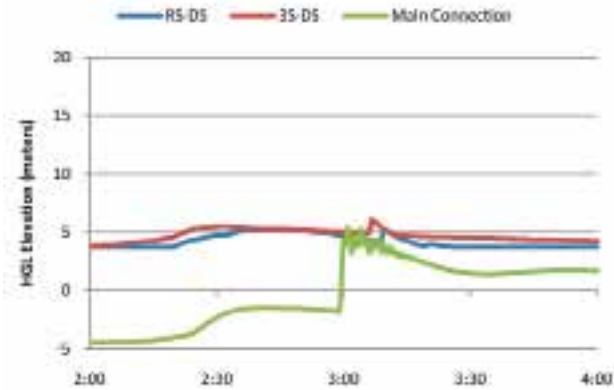
### Thames Tideway

The Thames Tideway project, in London, England, consists of deep tunnels that, like the DCWASA tunnels, will store and convey large quantities of CSO for subsequent treatment. The London tunnels will also be constructed in phases, with the first phase (the Lee Tunnel) being completed by 2015 and the second phase (the Thames Tunnel) targeted for completion by 2020. The objective of these tunnels is to reduce the frequency and volume of CSO into the tidal River Thames and its tributaries within greater London. SHAFT modeling is being conducted to ensure that the Lee and Thames Tunnels will not experience excessive HGLs that cause flooding to grade or backups in the existing collection system, to predict venting rates at relief points and to identify locations where trapped air pockets may develop.

The London Tideway tunnels (LTT) system will consist of about 29 km (18 miles) of 7.2 m (24 ft) main tunnel and 9 km (5.6 miles) of connection tunnels ranging in size from 2.2 m to 4.5 m (7.2 to 14.7 ft). They will be constructed in con-

**FIG. 9****Propagation of bores in non-surcharged tunnel.**

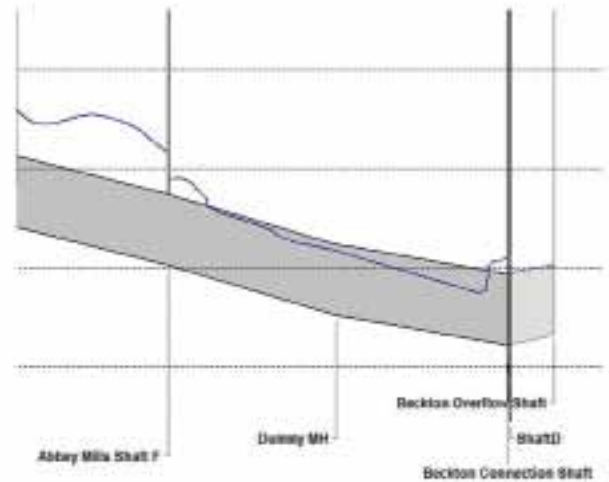
junction with significant capacity expansions of two major treatment works. With a total storage volume of nearly 1.15 Mm<sup>3</sup> (40.6 million cu ft), the completed system will capture about 96 percent of the typical year CSO volume and reduce spills to fewer than four events per year. Analysis of tunnel performance has focused on inflows produced from rainfall corresponding to a 15-year, two-hour event, which, when applied to the entire catchment area at the same time, was equivalent to a 50-year event at a more local scale. These simulated flows include both pump station output as well as flows routed to the tunnels by collection tunnels and CSO

**FIG. 10****Time series of HGLs corresponding to Fig. 9.**

consolidation structures. As much of the existing collection system is capacity-limited, larger events are not expected to deliver significantly greater peak flows to the tunnels.

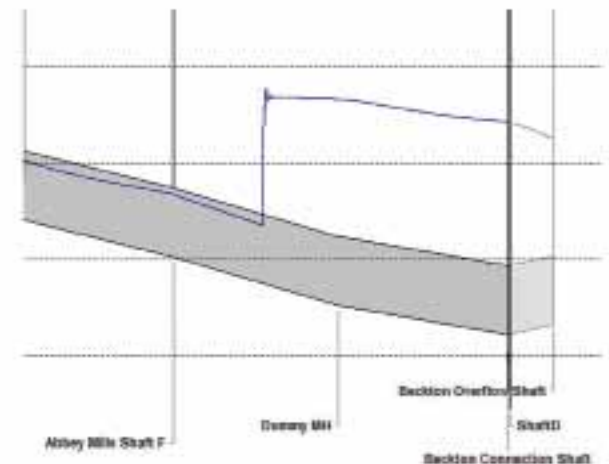
Inflow hydrographs came from a link-node model of the existing London collection system, which included the tunnel system so that some interaction between it and the existing system could be simulated. This approach aided in the evaluation of real-time controls for limiting inflow to the tunnel, which became more important after the initial SHAFT simulations, as discussed later. Flows were delivered to the tunnel through more than 20 inlets, the exact number depending on the arrangement of tunnel geometry under each scenario. Flap gate closure was also simulated based on simulated water levels in drop shafts rising above collection basin elevations.

The SHAFT model identified issues with the various tunnel geometry arrangements during the 15-year storm event, including premature pressurization and excessively high HGLs at locations along the Thames, generally around the farthest upstream reaches of the tunnel. An example of premature pressurization is shown in Fig. 11, which focuses on a large air pocket that has formed at the lower end of the tunnel due to surcharge conditions near Abbey Mills Shaft F. As noted previously, premature pressurization is essentially a result of “too much, too soon,” so mitigation efforts looked at limiting the total inflow to the tunnel. The peak composite inflow rate (that is, all sources added together) for the 15-year event was nearly 390 m<sup>3</sup>/s (143 cu in./min), compared with 290 m<sup>3</sup>/s (106 cu in./min) for the two-year event, which did not result in premature pressurization. Based on this comparison, it was proposed to determine caps on inflow rates at key locations, such that the peak composite inflow rate would not exceed 290 m<sup>3</sup>/s (106 cu in./min). After various trials, workable solutions were found, including the scenario shown in Fig. 12. This pipe-filling bore, while still a force to be reckoned with, is nowhere near the problem posed by the 4-km- (2.5-mile-) long air pocket seen in Fig. 11. Limiting the inflows makes better use of the tunnel volume by avoiding flooding to grade from surge-induced wide variation in HGLs, as well

**FIG. 11****Example of premature pressurization showing air pocket.**

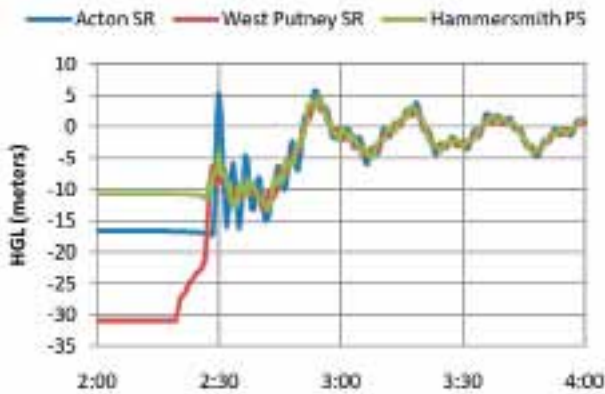
as preventing geysers caused by air pocket exhaustion. In practice, the inflow caps determined in the modeling do not have to be absolute at every location. When rain is more localized, individual inflow locations could exceed the caps as long as other locations are not filling, or filling at reduced rates. The challenge for real-time control is to keep an eye on the total inflow rate to the system.

A re-evaluation of real-time inflow controls produced a filling scenario without premature pressurization. But there were still high HGLs at the upstream end of the tunnel system to contend with. Various construction constraints at the surface meant that HGLs more than a few meters above grade could not be tolerated. For modeling purposes, an elevation of 2 m (6.5 ft) was considered the absolute maximum at these locations. Figure 13 shows time series at certain potentially problematic locations, from a SHAFT simulation in which HGLs were allowed to rise as high as

**FIG. 12****Premature pressurization avoided through inflow controls.**

**FIG. 13**

**HGL time series showing bore impact and subsequent reflections.**



momentum would allow. The Acton Storm Relief junction represents the furthest upstream point in the tunnel, and is actually at the end of a 2.2-m- (7.2-ft-) diameter tunnel that is elevated relative to the main 7.2-m- (23.6-ft-) diameter tunnel. The spike at 2:30 represents the bore striking this upstream point, with the subsequent surges due to reflections of this pressure wave off other structures — essentially the entire tunnel contents are sloshing back and forth after filling.

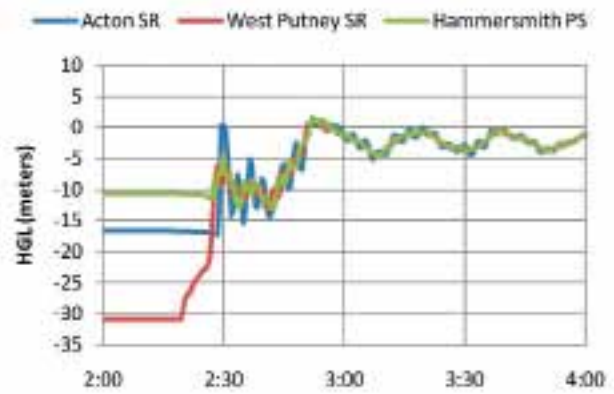
The initial approach to mitigating these peak HGLs was to place overflow relief points at the locations experiencing the highest HGLs and to determine two things: whether overflow relief would be enough to attenuate excessive HGLs at other locations, and just how much water would spill from these points. Figure 14 shows the result of this model run, in which five relief points were modeled by adding overflow weirs at an elevation of zero meters. The locations shown in the figure represent the highest peaks in the entire system and none was above 1.8 m (5.9 ft). The total volume spilled in this scenario was nearly 6,400 m<sup>3</sup> (226,000 cu ft), however, which is not a trivial volume to contain at the surface, at least not in the densely populated

**FIG. 14**

**HGL time series showing attenuation of impact and reflections.**

**FIG. 15**

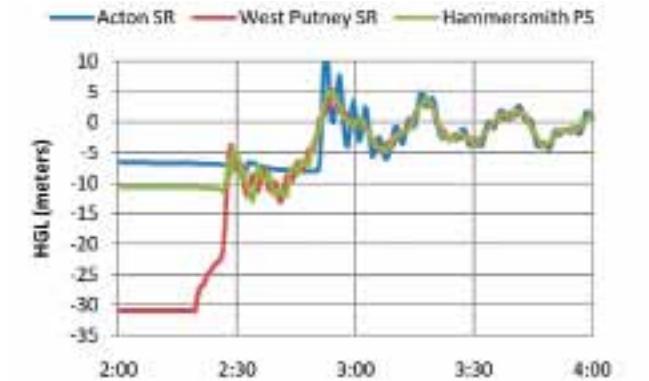
**HGL time series showing reduced initial bore reflection with high surges.**



London area. Subsequent simulations involved placing overflow points at different locations and upsizing the smaller branch tunnel to Acton. It was found that by increasing the diameter of the Acton spur to 4.5 m (14.7 ft) (noting that this diameter was in use at other locations) and consolidating the storage to two locations, similarly acceptable peak HGLs could be achieved with a total overflow volume of only 620 m<sup>3</sup> (21,900 cu ft).

Figure 15 shows the results of another run in which the Acton spur was raised another 10 m (33 ft) relative to the main tunnel, so that the initial bore would reflect off the dropshaft instead of making its way into the spur. No overflow relief points were included in this run, so its results could be directly compared with the results shown in Fig. 13. While raising the Acton spur does indeed remove that first spike seen at 2:30, there is still a major surge that reflects through the system and leads to excessive peak HGLs at the other locations. In fact, the initial HGL spikes at Acton are even higher than when the spur tunnel was at its original elevation. As it turned out, raising the spur was not viable from a construction standpoint. But the simulation shows how SHAFT can facilitate analysis of novel solutions.

**FIG. 15**



## Conclusions

SHAFT is a very useful computational tool to evaluate alternatives for mitigating surges and trapped air in large diameter tunnel systems. SHAFT's innovative computational approach for simulating open channel and pipe-filling bores, hydraulic transients and location of trapped air pockets helps users to quickly determine potential problem areas in proposed or existing tunnel systems and to assess solutions. Every step of the way, the simulations for the DCWASA and London Tideway Tunnels systems have provided designers with peak HGLs, peak venting rates and locations of large air pockets. Further, the tunnel designs have been adapted to minimize the effects of surges and trapped air to reduce the risk of failure under extreme filling and increase everyone's confidence that expensive retrofit solutions will be avoided. (References available from the author.) ■