A Tale of Two Capitals: Modeling Helps Designers Manage Strong Surge and Pneumatic Forces in Deep Combined Sewer Storage Tunnels

Daniel J. Lautenbach, John K. Marr and Peter Klaver
LimnoTech, Ann Arbor, MI, USA

John F. Cassidy
Greeley and Hansen, Washington, DC, USA

David Crawford
London Tideway Tunnels Delivery Team, London, England

ABSTRACT

Rapid advancements in tunneling technology and the need to avoid surface disruptions have made deep tunnels popular options for dense urban areas to store and transport large volumes of untreated combined storm and waste water. The District of Columbia and Thames Water Utilities (London) have selected large branching tunnels to capture combined sewage for treatment. Rapid filling is a given for these types of systems and presents many design challenges due to the massive forces involved. Wastewater geysers, blown manholes- even structural failures can result if not adequately considered. Advanced computer modeling used to help designers avoid these problems in Washington and London is showcased.

The District of Columbia Water and Sewer Authority (DCWASA) and Thames Water Utilities (TW) are each designing large tunnel systems to meet pollution control requirements and reduce flooding potential. Plans for both national capitals are to rapidly design, construct and put the tunnel systems in operation. An innovative computer model, based on research by Vasconcelos and Wright, has been simulating rapid filling, transient surges and pneumatics as an integral part of the evaluation of the tunnel designs, particularly in managing or controlling adverse conditions. The tunnel model, called SHAFT, simulates both open-channel and pipe-filling bores, the flows and forces at work and predicts locations and volumes of air entrapment and displacement. The model uses a novel shock capturing technique to simulate both flow regimes and the transitions from open channel to closed conduit flow. The model further predicts where air will be trapped in otherwise unexpected portions of the interconnected tunnels due to the piston-like action of hydraulic surges, the timing of different surges and wave reflections. Model results for a matrix of hydrographs, initial fill levels, control alternatives and tunnel profiles have been used to adjust the location and sizing of drop shafts and vents to avoid dramatic sewage geysers and loud air releases in both capitals. Some general lessons learned are presented and discussed that will be informative to tunnel designers elsewhere.

KEYWORDS

Surge, Hydraulic Transients, Geyser, Tunnel Design, Sewer Analysis, Unsteady Flow, Pneumatics, combined sewer overflows.

INTRODUCTION

Combined sewer overflows are major sources of contamination to urban rivers and streams (U.S. Environmental Protection Agency 2004a; CIWEM, 2004). Combined storm water and sanitary sewer systems are especially prevalent in older cities of the Northeastern and Midwestern U.S. and in England. During wet weather events, total inflows to these systems exceed wastewater treatment capacity and are discharged untreated to surface waters. U.S. CSO policy requires cities to implement Long-Term CSO Control Plans (LTCPs) sufficient to meet water quality standards or meet presumptive criteria, which include overflow frequency and/or percent of flow captured and treated (U.S. Environmental Protection Agency 2004b).

Sewer separation is expensive, often leads to an increase in pollutant loadings, and is disruptive for urban communities; most communities look to storage of wet weather flows to meet the regulatory requirements and CSO policy. If storage facilities are properly sized, storm flows for many rain events can be captured and routed to wastewater treatment after elevated storm flows have subsided. Sizing improvements to minimize overflows and maximize capture can be based on watershed modeling of representative events to simulate flows entering the system, combined with hydraulic modeling to route flows through the sewer system. Computer programs to perform these simulations are widely used and well developed. Many communities (including Chicago IL, Minneapolis MN, Portland OR, and Toledo, OH) have installed storage tunnels, and others like Washington, DC and London, England are including tunnels in their CSO control plans. Attractive attributes of tunnels include economies of scale and generally lower community impacts.

As storage and conveyance tunnels fill, it is also important to consider the potential effects of transient surges, including high hydraulic grade lines (HGLs), geysering caused by trapped air, and the forces created by rapidly moving bores. Predicting these transient impacts is beyond the capabilities of the watershed and collection system software packages mentioned above. Accurate simulations of rapid filling dynamics are important to prevent accidental venting of captured sewage, to ensure the safety of tunnel operators and the public, and to prevent damage to sewer system and tunnel infrastructure.

In collaboration with scholars at the University of Michigan and the University of Brasilia, LimnoTech developed a software program entitled SHAFT (Surge and Hydraulic Analysis for Tunnels). SHAFT simulates all stages of the tunnel filling process, including the creation of and transitions between open channel and pipe filling bores as the tunnel fills and the locations prone to air entrapment.

The District of Columbia Water and Sewer Authority (DCWASA) is designing a large tunnel system to capture and store combined sewage generated in the City of Washington for later treatment, as is the Thames Water Utilities (TW) serving London, England. The SHAFT model is being used in both capitals to simulate transient hydraulic grade lines and air pocket formation for planned tunnel geometry, using a variety of tunnel filling and dewatering scenarios. These simulations support and test surge control strategies and the adequacy of design modifications to prevent adverse impacts of tunnel-filling surges, insure the needed CSO control and avoid costly oversizing.

This paper briefly describes the SHAFT modeling framework, contrasts its structure and performance with pre-existing transient surge models, and presents sample results and lessons learned from transient surge modeling performed to support designs for the Washington and London tunnel systems.

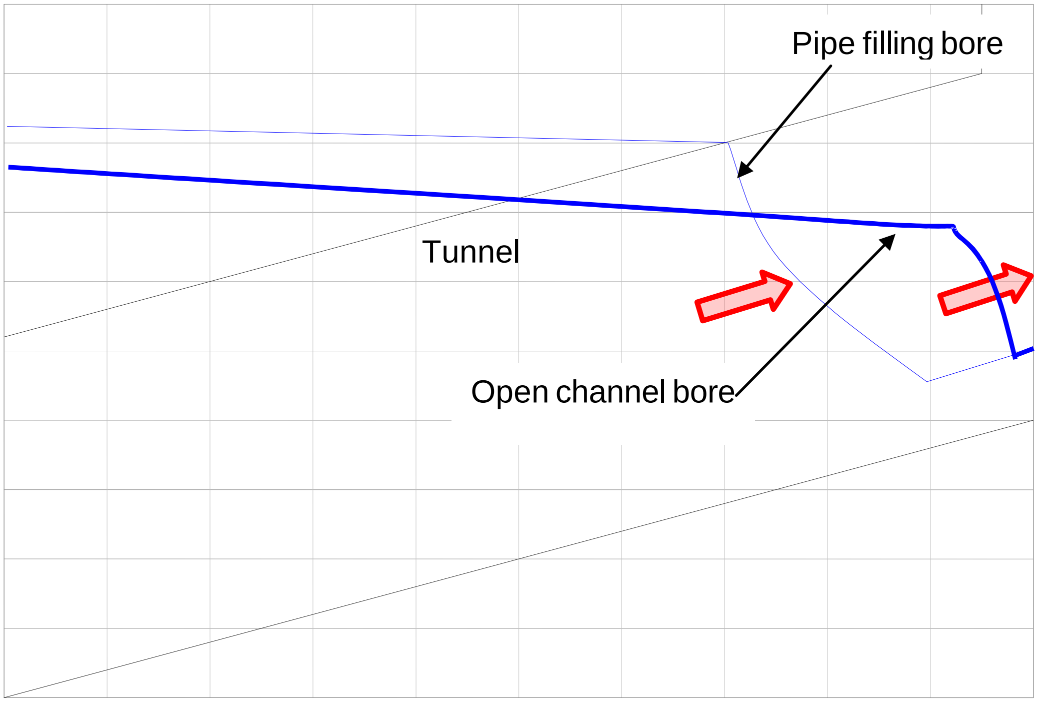
SURGE MODEL FRAMEWORK

Overview of the Rapid Filling Problem in Tunnels

Non-steady flow during rapid filling of sewer system storage tunnels produce shock fronts that stress physical structures and can result in discrete pockets of entrapped air, often associated with bore reflections from tunnel transitions. These fronts can take the form of either pipe-filling bores (PFBs) or open channel bores. These fronts are flow discontinuities that move through the tunnel system like a moving hydraulic jump. The discontinuity can reach from open water in the tunnel to the crown of the pipe (a PFB) or can create a jump in the water surface itself, without pressurizing the tunnel (an open channel bore). These bores, illustrated in Figure 1, can strike the end of a tunnel with tremendous force, and drive air and entrained sewage upwards into dropshafts encountered along the length of the tunnel. If there is a sufficient surge in the resulting hydraulic grade line (HGL), flooding to grade and backups at low points in the collection system can occur (Guo and Song, 1990).

An open channel bore, as shown by the thicker line in Figure 1, can cause the problems described above, and in addition can trap pockets of air when this bore reflects off a tunnel transition point or meets another bore within the system. When air pockets are not ventilated, they reduce the volume of CSO storage available, and also reduce the conveyance capacity of the tunnel. Air is compressible, so a rapid increase in pneumatic pressure can occur when the air pocket is squeezed by water in the tunnel (Zhou et al., 2002). In addition, trapped pockets of air rise rapidly when they migrate to points in the tunnel that are accessible to the surface. The rapid rise of air at access points that are already partially filled with captured sewage can push captured sewage upwards, resulting in buoyancy-driven geysering. This geyser effect is different than the phenomenon of high peak HGLs at dropshafts mentioned above, and depends both on the size of the trapped air pocket and the geometry of structures that would provide venting. Vertical shafts that have a relatively small cross sectional area can inhibit the downflow of water past the escaping air as it rises, and these are more prone to geysering. Therefore it is important to determine both the sizes of pockets and locations where they form, and evaluate venting points near these locations.

Figure 1 - Comparison of Pipe Filling and Open Channel Bore Hydraulic Grade Lines



Model Development

In collaboration with scholars at the University of Michigan and the University of Brasilia, LimnoTech developed a surge modeling tool named SHAFT (Surge and Hydraulic Analysis for Tunnels). SHAFT is based on a program of research by Vasconcelos and Wright (all citations) into methods of numerically simulating surge behavior in tunnels. SHAFT simulates both open channel and pipe-filling bores, and predicts locations of air entrapment. The model utilizes a shock capturing solution technique that decouples hydrostatic pressure due to water depth in the conduit from surcharge pressures occurring only in pressurized conditions, and takes advantage of the structural equivalence between unsteady incompressible flow equations in elastic pipes and unsteady open channel flow equations in the model governing equations. These two concepts allow SHAFT to simulate both flow regimes using the same generalized set of equations, and to readily model flow transitions (i.e. from open channel flow to closed conduit flow) (Vasconcelos et al., 2006). Predictions from the more widely applicable method used in SHAFT have even been compared for pressurized flow situations fitting the more narrowly applicable Method of Characteristics models and the results are favorable where the two methods should agree. (Vasconcelos and Wright, 2007).

SHAFT implements a non-linear finite volume numerical scheme that utilizes an approximate Riemann solver applied to the Saint Venant unsteady flow equations. This approach was adapted from finite volume method schemes that have successfully used Riemann solvers for other highly dynamic fluid flow problems. The use of a nonlinear numerical scheme minimizes problems associated with smearing of flow discontinuities associated with shock phenomena such as hydraulic bores. The benefits of using a non-linear scheme such as the one employed in SHAFT have been demonstrated by Machione and Morelli (2003).

Air is currently represented in SHAFT as void space; that is, volume not occupied by water. A PFB tends to expel all trapped air at upstream vent shafts, assuming there is sufficient venting capacity, but the reflection of the bores from ends of tunnels can result in discrete trapped air pockets, and both phenomena are simulated by SHAFT. This identifies locations and sizes of vent shafts needed at intermediate locations, in addition to ventilation that may be needed at the ends of tunnels and thereby avoids buoyancy-driven geysering of water in the path of migrating air pockets.

Laboratory Studies

The SHAFT model formulation was developed and favorably compared to data from extensive laboratory testing of scale models in the University of Michigan hydraulics lab, which included both PFB and sub-PFB filling conditions. The approach of that work was to generate a wide range of filling behaviors in a physical model of a tunnel system and then develop a numerical model that could accurately reproduce them (Vasconcelos and Wright, 2005; Vasconcelos et al., 2006). The ability of the SHAFT model to predict a flow regime transition from free surface flow to pressurized flow that is not coincident with the movement of an open channel bore gives the model the ability to realistically define tunnel dynamics under a variety of inflow scenarios and to predict large air pockets that can cause geysers if not vented appropriately (Wright et al., 2007). The model framework has also been compared to laboratory and numerical studies by others. The SHAFT model framework simulates the full range of conditions and shows good agreement with the results of these laboratory and numerical studies that were focused each on narrow transient flow situations (Vasconcelos and Wright, 2007). This model can therefore be used confidently and can negate the need for more expensive physical models.

DISTRICT OF COLUMBIA SYSTEM

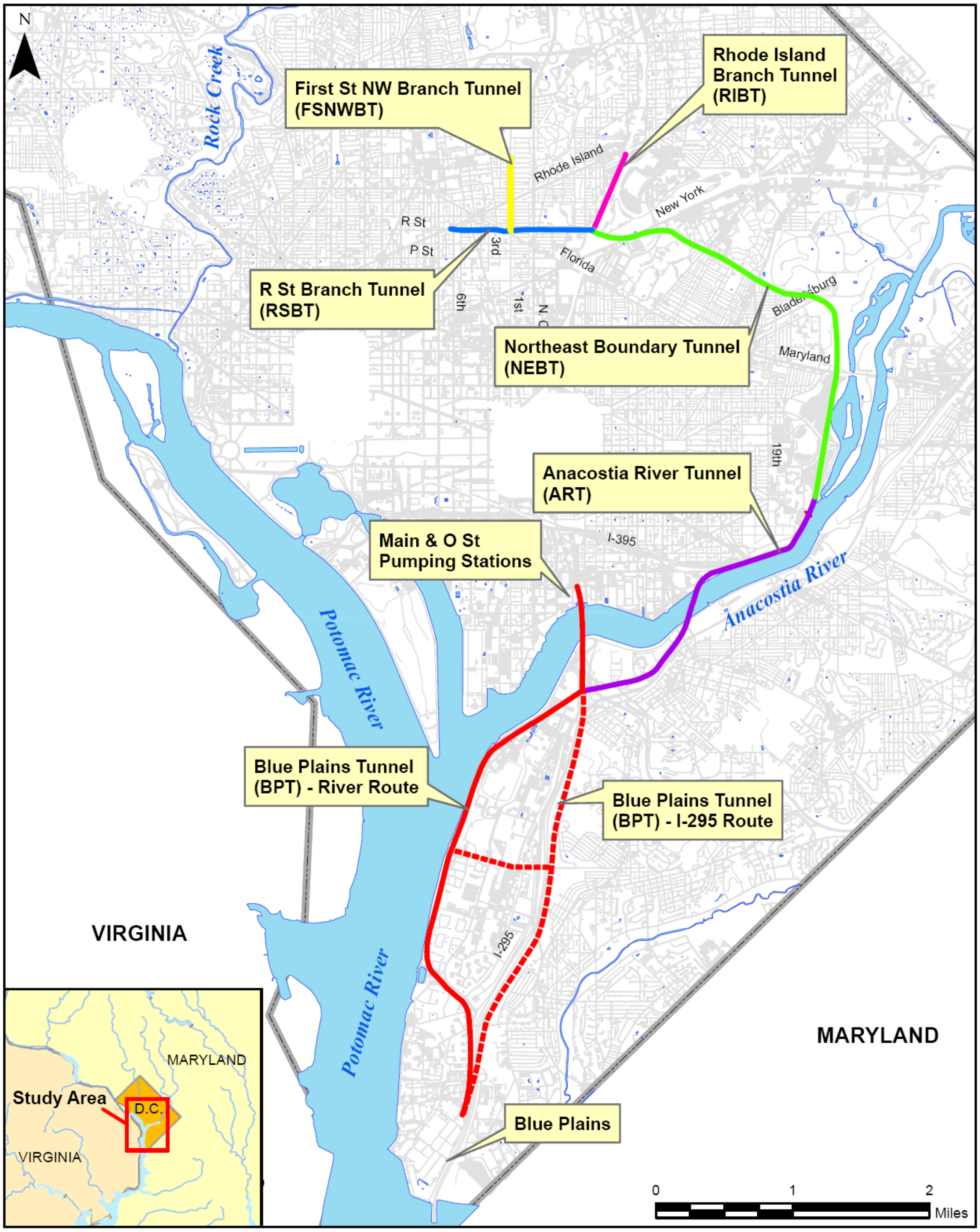
The DCWASA LTCP (2002) includes a range of controls to reduce the volume of combined sewage overflow (CSO) to receiving waters in an average year from approximately 2.5 billion gallons (with current in-system controls fully operational) to 138 million gallons per year; the controls will also reduce the number of overflow events from 75/74/30 overflows per year in the Potomac, Anacostia and Rock Creek receiving waters (currently) to 2/4/4 overflows per year under the LTCP. Capture of combined sewer flows in storage tunnels includes a 49 million gallon storage tunnel from Poplar Point to the Northeast Boundary Outfall and a 77 million gallon storage and conveyance tunnel parallel to the Northeast Boundary Sewer. These tunnels were also designed to relieve flooding in sections of the city and provide a higher level of control for design storms not reflected in the average year CSO statistics. The proposed tunnel system has since been extended in a plan supplement (DCWASA, 2007) to include a tunnel from Poplar Point to the DCWASA Blue Plains advanced wastewater treatment plant. The expansion increases total tunnel storage from 126 million gallons to 157 million gallons, and the apportionment of that volume among the various tunnel sections is to be determined in the course of detailed facilities planning. The additional tunnel storage was added to reduce total nitrogen discharge and meet a new requirement that was not in effect at the time the plan was finalized.

Tunnel Layout and Inputs

Several vertical and horizontal tunnel alignments were developed to intercept 14 CSOs that would otherwise discharge to the Anacostia River and to provide flooding relief to sewers in the Northeast Boundary Drainage area. Factors causing geometry changes included the addition of the Blue Plains Tunnel (BPT) that will connect the

Anacostia River Tunnel (ART) to the Blue Plains WWTP, geotechnical conditions encountered in the field, tunnel constructability, siting and accessibility concerns, desire to maximize storage of the system built in 2025 below an elevation of 3 feet above sea level, high HGLs predicted during modeling of early designs, and simulated tunnel responses to extreme events. Of these factors, the simulated HGL responses to peak events required the greatest modifications to model geometry. The geometry simulated in the SHAFT model of the DCWASA tunnel system evolved throughout the modeling process and guided tunnel design. Tunnel geometries naturally also varied depending on the route of the BPT. Modeled tunnels included the Northeast Boundary Tunnel (NEBT) and associated spur tunnels, the ART, and the BPT. As modeled the Complete Tunnel System to be built by 2025 consisted of approximately ten miles of 23 foot diameter tunnel and three miles of spur tunnels ranging from 8 to 15 feet in diameter. Simulations were performed for two basic configurations: the “Complete Tunnel,” consisting of all three component tunnels, and the “Intermediate Tunnel,” consisting only of the ART and BPT. The Intermediate Tunnel will be constructed first, and is expected to be operational on its own while the NEBT and associated spurs are constructed in a second phase. Horizontal alignments for the proposed system are shown in Figure 2.

Figure 2 – Horizontal Alignments of Proposed DCWASA Tunnel System



Flows used to drive the SHAFT filling scenarios were generated using a hydrologic/hydraulic model of the DCWASA collection system. Simulated flow into and out of dropshafts was regulated in several ways. Flows to the tunnel system were modeled as free-flowing outfalls in the collection system model; that is, no backwater effects produced by a full tunnel were simulated. However, inflows to SHAFT were restricted where applicable, either by flap gates that closed at specific elevations, or by head-based diversion curves that were developed independently. Flow out of drop shafts (and from the tunnel) were simulated either by free-flowing weirs, or by head-discharge curves that were developed for various overflow points, based on river water surface elevations; several outfall conditions were simulated including the 10-year flood and 100-year flood river surface elevations. SHAFT scenarios used hydrographs of storm frequencies ranging up to the 100-year, 6-hour event, including possible future connections and inflows to the tunnel system that may be added when the Complete Tunnel System begins operation in 2025.

Conditions Simulated

The conditions simulated could be varied in three essentially independent ways: tunnel layout/geometry, filling scenario, and river surface elevation. Simulation conditions that were evaluated in coordination with the DCWASA tunnel designers as part of the surge modeling process included the following:

- several storms taken from 1988 to 1990 that generated the largest CSO response in the collection system;
- tunnel filling for the 15-year, 6-hour storm inflow hydrographs for present and future wastewater flows;
- tunnel filling for the 100-year, 6-hour storm hydrographs for present and future wastewater flows;
- partial fill antecedent conditions i.e. the tunnel is incompletely de-watered from a previous rainfall event;
- scenarios using the 10-year and 100-year Potomac and Anacostia river surface elevation;
- simulations of a large storm moving west to east across the drainage area; and
- BPT tunnel route following I-295 and one following the Potomac River.

Among all of the resulting simulations, the 100-year, 6-hour storm events for the Complete Tunnel System with future flows caused the largest concern in predicted tunnel performance, with initial predictions of flooding to grade at several dropshafts at the upstream end of the tunnel system. Consequently, several different changes to tunnel geometry were evaluated to reduce peak HGLs. These changes in tunnel geometry can be broken out into the following categories:

- changes in the slope of the NEBT or other branch tunnels;
- changes in the vertical alignment of the NEBT tunnel and/or other branch tunnels;
- addition of offline storage at or increasing the sizes of various shafts at various elevations; and
- increasing the sizes of selected upstream spur tunnels to increase linear storage.

Results

The tunnel surge model was used to develop economical and passive design features that are predicted to successfully control hydraulic surge and pneumatic challenges in the DCWASA tunnel system in both the intermediate and full service area build-out situations. Steepening the NEBT to a slope of 0.0045 ft/ft and crown-to-crown vertical alignments of spur tunnels produced the greatest benefit in reducing peak HGLs in the upper sections of the tunnel system, and also reduced excessive HGLs due to reflections in other sections of the tunnel system as well.

Comparison of peak HGLs within the BPT and ART tunnels showed a potential for more severe HGLs while the Intermediate Tunnel is in operation and prior to the completion of other tunnel sections in 2025. These peak HGLs are short duration, and are primarily caused by the reflection of surge waves off the upper end of the ART tunnel before the CSO 019 overflow structure is engaged. Once the Complete Tunnel System is in operation, upstream storage within the NEBT and other high spur tunnels and the initiation of overflow to the Potomac and Anacostia Rivers before surge waves reach the upper end of the Complete Tunnel System serve to minimize the height of surge generated peak HGLs. Figures 3 and 4 show example model predicted hydraulic grade lines at the Blue Plains Pump station and another tunnel overflow location as a function of time for the Complete Tunnel System filling under the 100-year, 6-hour storm design scenario. Figures 5, 6, and 7 show the tunnel filling process for the same storm at two different stages before the tunnel reaches steady state conditions, and also approaching steady state after the tunnel has filled and is discharging to the Potomac and Anacostia Rivers.

Figure 3 - Hydraulic Grade Line as a Function of Time at the Blue Plains WWTP Pump Station During the 100-year 6-hour Storm

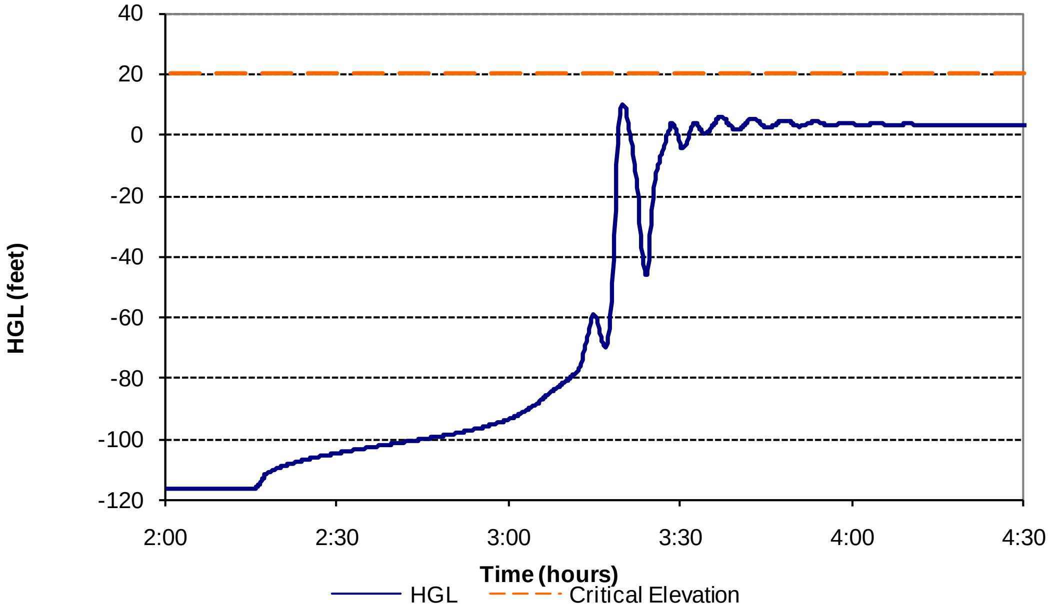


Figure 4 – Hydraulic Grade Line as a Function of Time at the Southerly CS0 019 Overflow During the 100-year 6-hour Storm

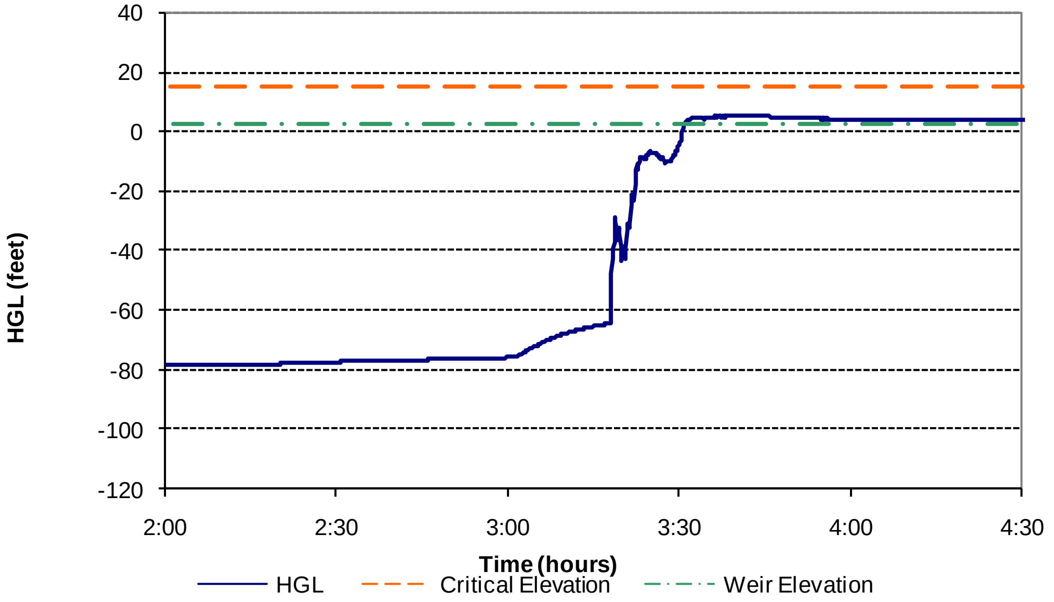


Figure 5 – Snapshot of the Hydraulic Grade Line in the Complete Tunnel System During the 100-year 6-hour Storm

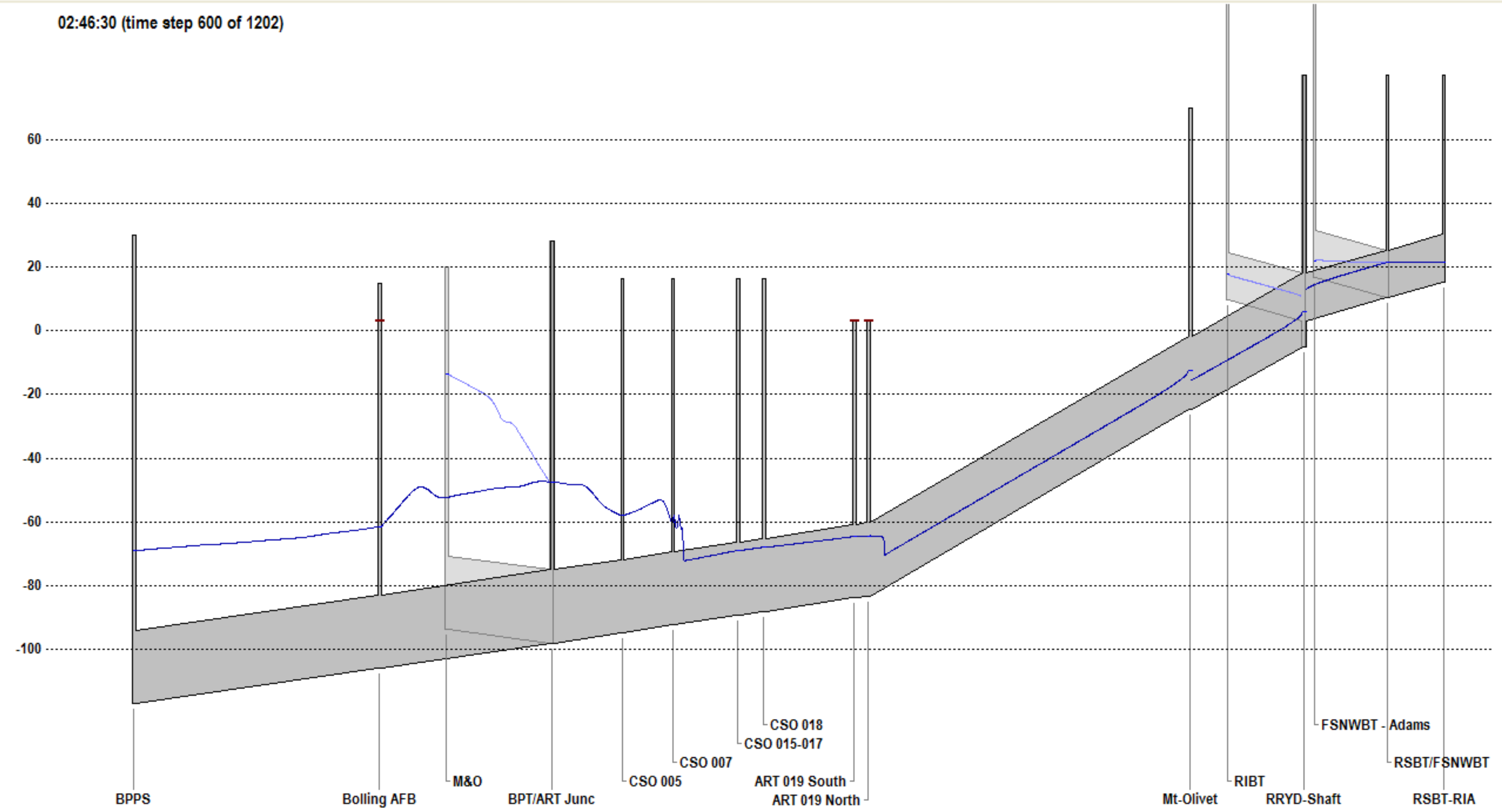


Figure 6 – Later Snapshot of the Hydraulic Grade Line in the Complete Tunnel System During the 100-year 6-hour Storm

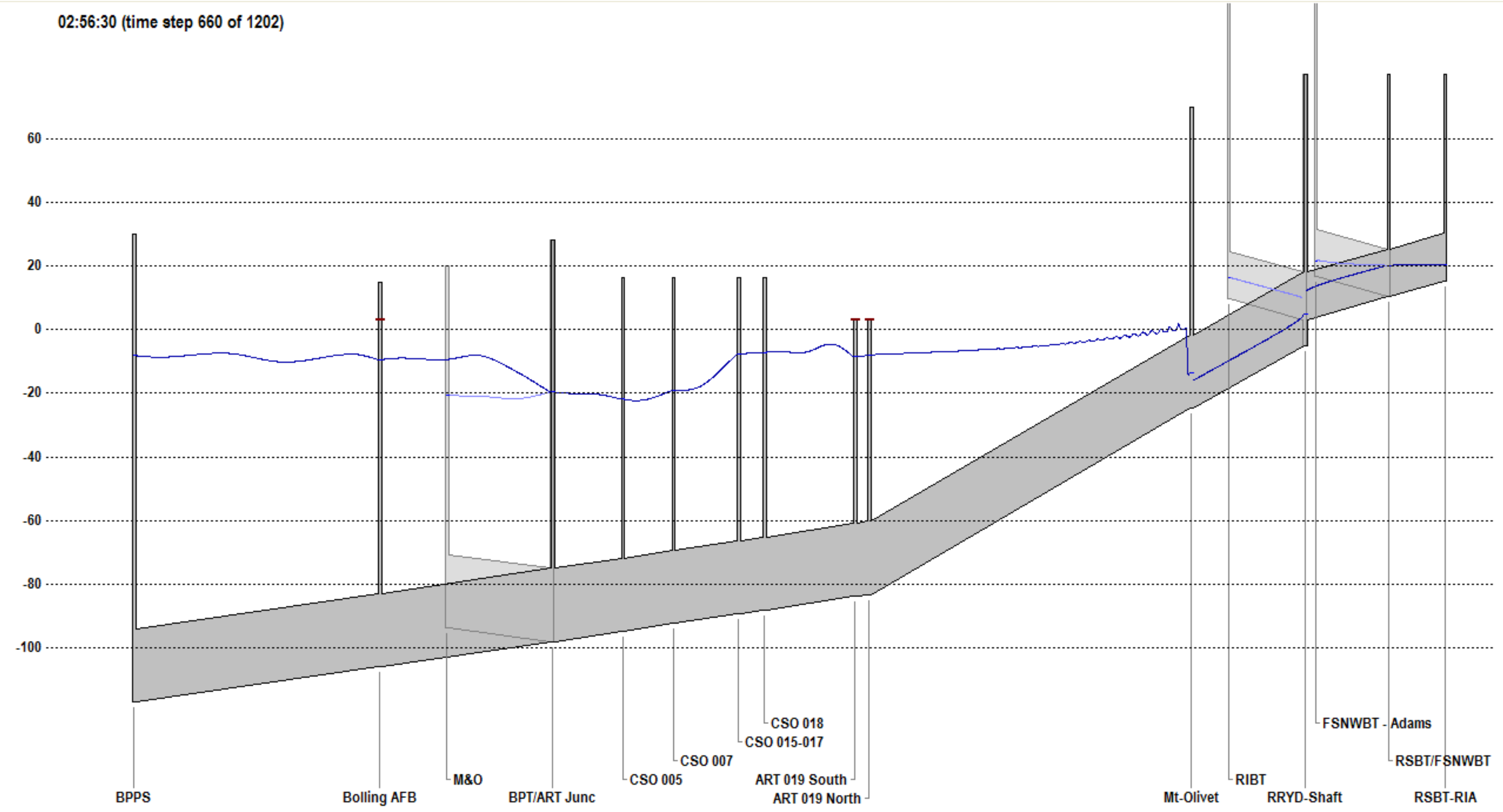


Figure 7 – Snapshot of the Hydraulic Grade Line in the Complete Tunnel System During the 100-year 6-hour Storm Approaching Steady State Conditions

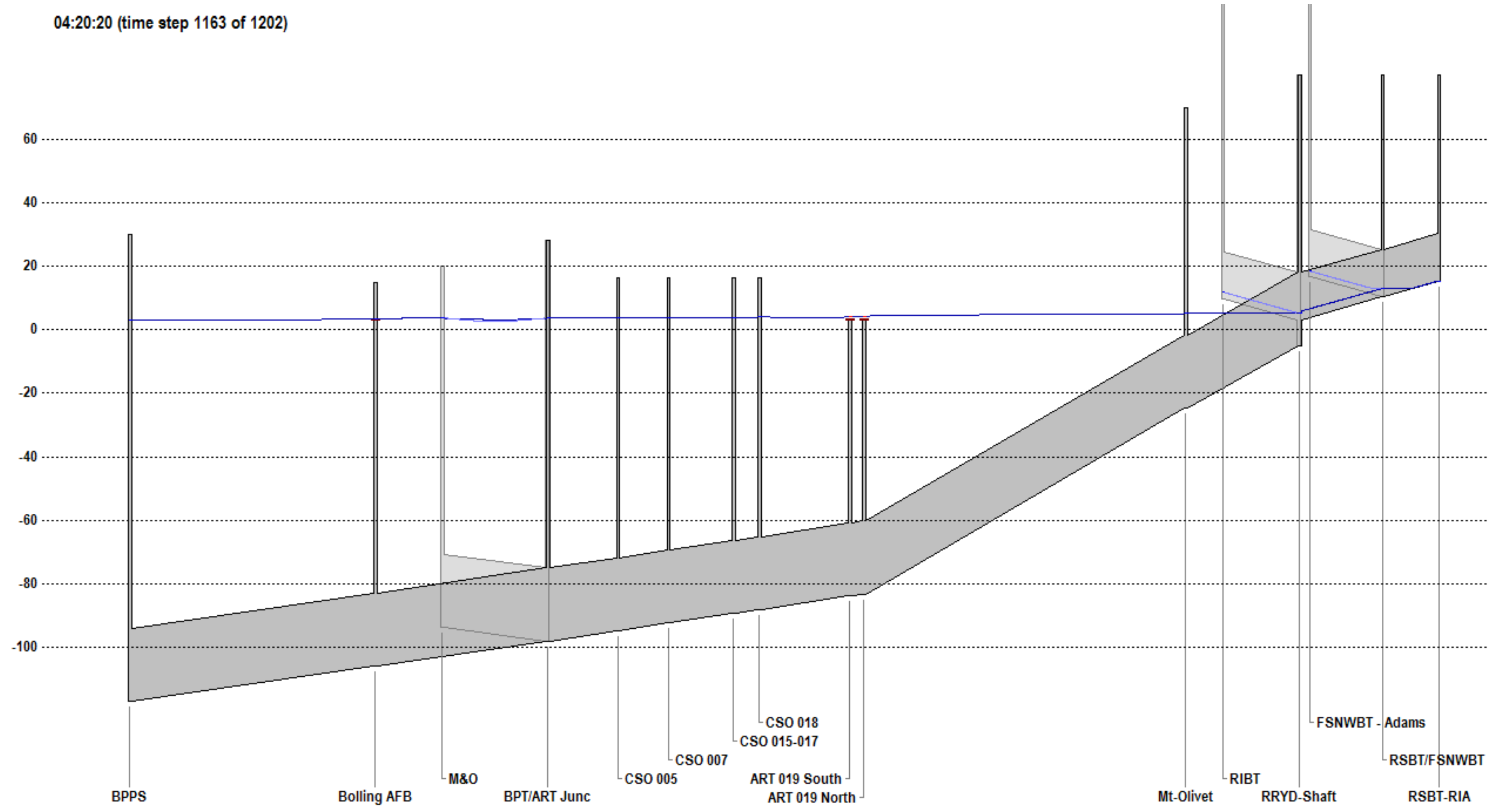


Figure 5 show two distinct bores: an open channel bore near the CSO 019 dropshaft and a second, pipe-filling bore just upstream of the CSO 007 dropshaft. Figure 6 shows that ten minutes later in the scenario, the second bore has caught up with first, and there is now a single pipe-filling bore approaching the Mt. Olivet dropshaft. In Figure 7 it is seen that inflows have receded, especially in the upper reaches of the NEBT (at the right of the figure), and the system is overflowing at CSO 019.

Other scenarios evaluated included various combinations of the filling scenarios and river surface elevations listed previously. None of these additional conditions resulted in adverse HGLs or surge conditions. The entire suite of tunnel-filling scenarios listed above was also evaluated using the BPT I-295 route for both the Intermediate and Complete Tunnel System.

Maximum HGLs between Drop Shafts

Maximum HGLs between shafts were also determined using the SHAFT model simulation of various tunnel filling scenarios. Figures 8 and 9 show the maximum HGLs for the 100-year storms in both the Intermediate Tunnel System and Complete Tunnel System for the BPT River Route. Predicted peak HGLs within the tunnel rise higher than predicted peak dropshaft HGLs. This is primarily because dropshafts have storage available to mitigate pressure spikes due to hydraulic transients caused by the filling process, whereas tunnel sections do not have extra storage if they are already filled when the transients occur. Similarly, peak tunnel HGLs rise higher in the Intermediate Tunnel simulations than in the Complete Tunnel simulations within the common sections since the steeply sloping section of the NEBT dampens peak HGLs for the entire system. In the Intermediate Tunnel System, surge waves that reach the upstream of the tunnel under extreme storms reflect and cause pressure spikes in the tunnel.

Minimum Gage Pressures

The SHAFT model was used to predict negative pressures in the tunnel system, which can occur when surge waves are reflected through reaches that are already surcharged. Although highly transient, the magnitude of these pressures is of interest because of the stresses they impose on the tunnel walls. Figure 10 shows the composite maximum vacuum pressures in the Intermediate Tunnel System for the 100-year event. The strong negative gage pressure in the section between CSO 019 and CSO 018 occurs after an open channel bore reaches the upstream end of the tunnel, reflects off the upstream end and travels back downstream as a pipe filling bore. Meanwhile, a second pipe filling bore develops, traveling up towards CSO 019, and these two bores collide in the tunnel between CSO 018 and 019, creating a large pressure spike in the now completely surcharged tunnel. When this surge wave reaches CSO 018 it is reflected back up the tunnel toward CSO 019 as a negative pressure surge. The negative pressures shown in the figure below do not occur at the same time and do not take up a large portion of the tunnel section between CSOs 018 and 019 at any one time. Nor do they occur for very long; the passage of the negative surge takes less than 10 seconds to pass from dropshaft to dropshaft. This figure also shows that the Main & O Pump Station branch experiences negative surge waves in these simulations as well.

In general, the most extreme minimum gage pressures calculated by the model occur when two bores meet within a tunnel segment away from a dropshaft. Model simulations showed that spur tunnels were more likely to experience negative gage pressures during extreme filling events, as well as the section of tunnel bounded by the CSO 018 and 019 dropshafts when the Intermediate Tunnel system is in operation.

Figure 8 – Maximum HGL for Intermediate Tunnel BPT River Route: 100-Year Event

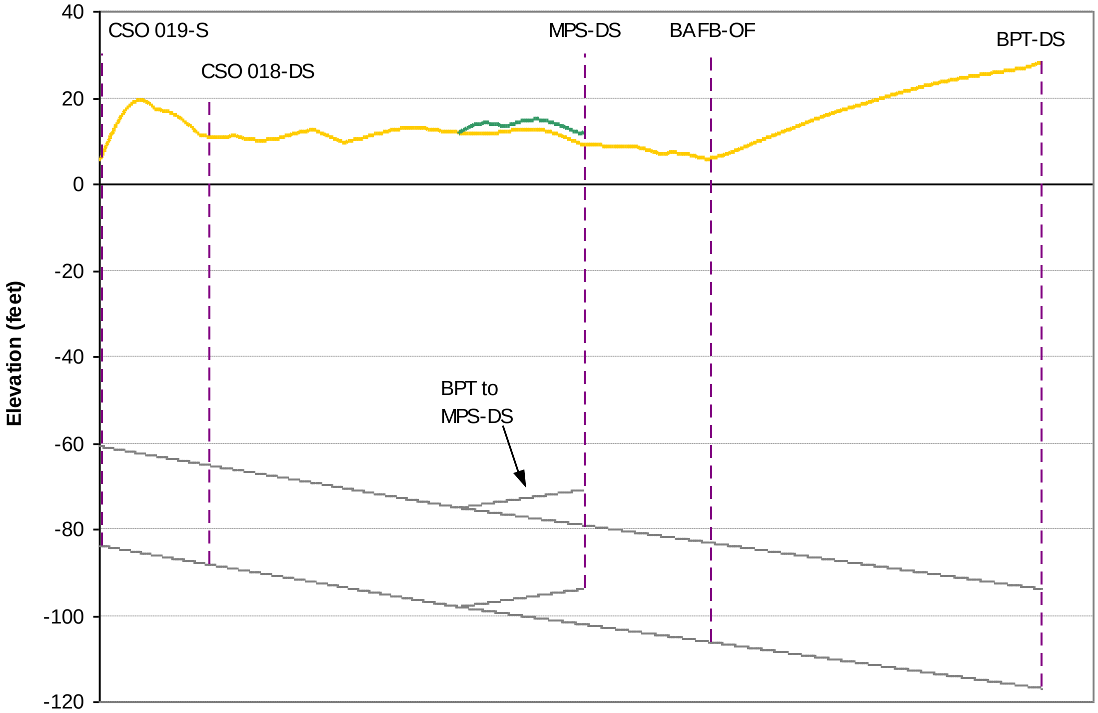


Figure 9 – Maximum HGL for Complete Tunnel River Route: 100-Year Event

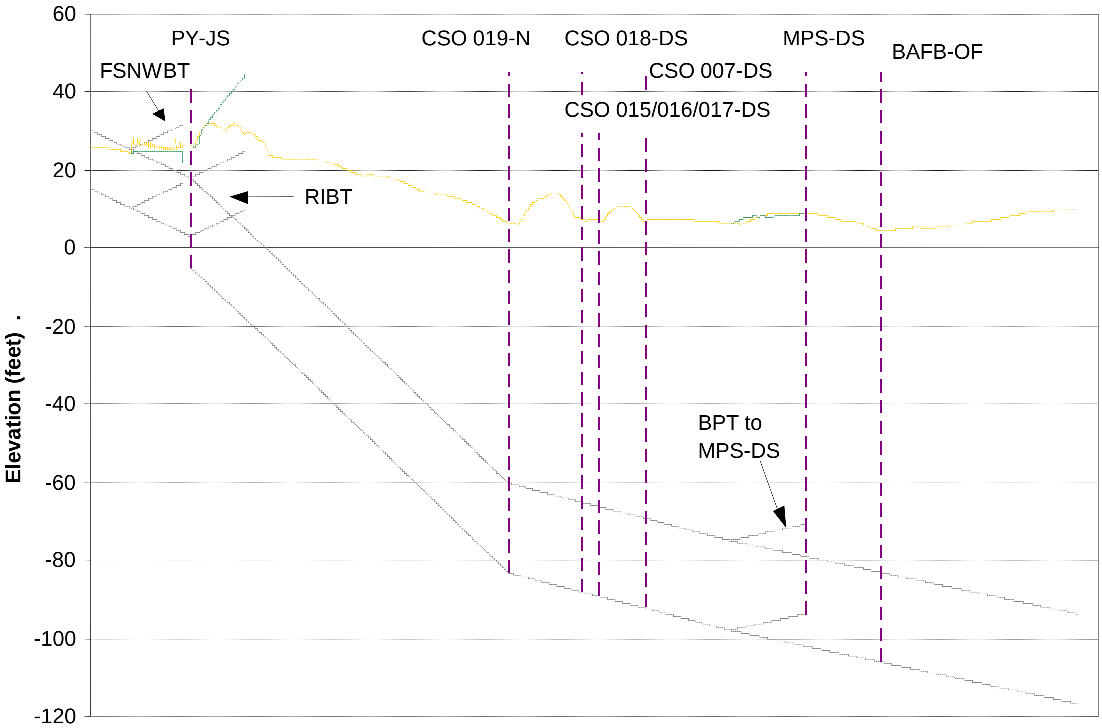
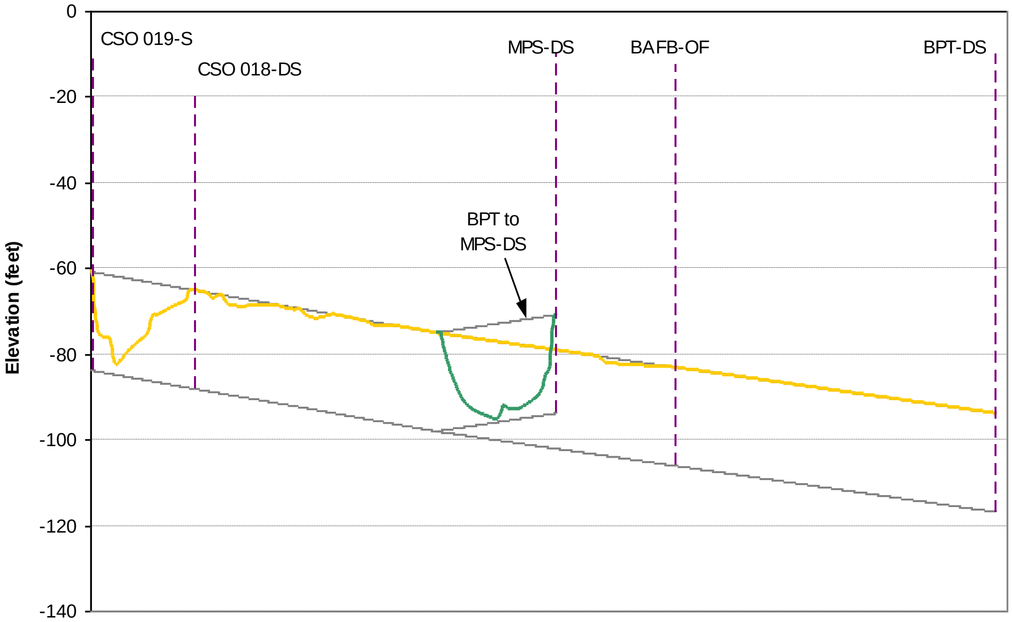


Figure 10 - Composite Minimum Gage Pressures Experienced Within the Intermediate Tunnel System During the 100 Year 6 Hour Storm (River Route)



SHAFT simulations have shown that surges and transients generated as part of the DCWASA tunnel filling process during extreme storms can be successfully mitigated through the selection of appropriate geometry. Current tunnel geometry successfully mitigates the possibility of the creation of large tunnel HGLs at most dropshafts during the tunnel filling process for the extreme events and critical conditions considered. Where model-predicted peak HGLs do temporarily rise above critical elevations, mitigation measures have been evaluated at selected dropshafts for both the Intermediate and Complete Tunnel systems, and solutions have been found using the SHAFT model. The following passive mitigation measures were considered or employed:

- Design the shaft to withstand the hydraulic pressure - The shaft structure and all openings are designed to take the predicted hydraulic pressure, plus a safety factor.
- Extend shaft above predicted surge elevation - For this option, the top slab of the shafts was extended above the predicted surge elevation, plus a freeboard allowance.
- Add storage at the shaft sites - This option involved adding storage to contain the predicted surge volume. When CSO influent rises during an extreme surge event, it overflows an annular weir and is contained in the surrounding temporary storage as part of the drop shaft. Any stored volume flows by gravity back to the tunnel.
- Planned surge relief to the river or to existing CSOs - The approach involved adding an overflow weir near the top of the shaft. When the surge overflows the weir, it is conveyed to an existing CSO overflow (if capacity were available) or to a new outfall to the river.
- Combinations - The above alternatives were also combined at some locations to get the most effective solutions.

Venting

Tunnel venting facilities must not only handle the large quantities of air displaced by water rapidly filling the tunnel, but must also provide for the venting of air pockets trapped by reflecting surge waves. In addition, water falling in the drop shafts will entrain air that also needs to be controlled. All predicted air pockets were reasonably small, and the oversized design of the drop shaft structures were predicted to provide sufficient relief for both trapped air pockets and for venting in general. Air management evaluations, including calculation of peak venting and inflow rates to the tunnel, as well as determining locations of large air pocket development, were performed. In the

Intermediate Tunnel System, air entrapment was predicted to occur primarily in the upper end of the tunnel system in the ART and the BPT. When the Complete Tunnel System is in operation, smaller pockets of air may be trapped in the same locations. The model also predicted that the NEBT could develop air pockets during filling at two locations: a short distance up-tunnel from the transition between the ART and NEBT, and a short distance downstream of the upstream end of the NEBT. Minimum vent and air intake areas were calculated using a peak acceptable air velocity of 3,000 ft/minute; the largest cross sectional area needed for venting at any vertical shaft was approximately 160 ft^2.

THE LONDON TUNNEL SYSTEM

Like the DCWASA tunnels, the London tunnels is a CSO storage and conveyance (to treatment) system. 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 combined sewer overflow 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, causing flooding to grade or backups in the existing collection system and to predict venting rates at relief points and locations where trapped air pockets may develop.

Tunnel Layout and Inputs

A layout of the Lee Tunnel operating alone, when it is completed in 2015, and several layouts of the Lee and Thames tunnels operating in concert were evaluated for this study. The various combined Lee and Thames layouts were designed to evaluate how different tunnel lengths, and arrangements of tunnel connections, would affect the filling process, storage volume captured and cost of construction. The London Tideway Tunnels (LTT) system will consist of about 29 kilometers of 7.2 meter main tunnel and 9 kilometers of connection tunnels ranging in size from 2.2 meters to 4.5 meters. The LTT, in conjunction with significant capacity expansions of two major treatment works, will capture about 96% of the typical year CSO volume and reduce spills to less than 4 events per year.

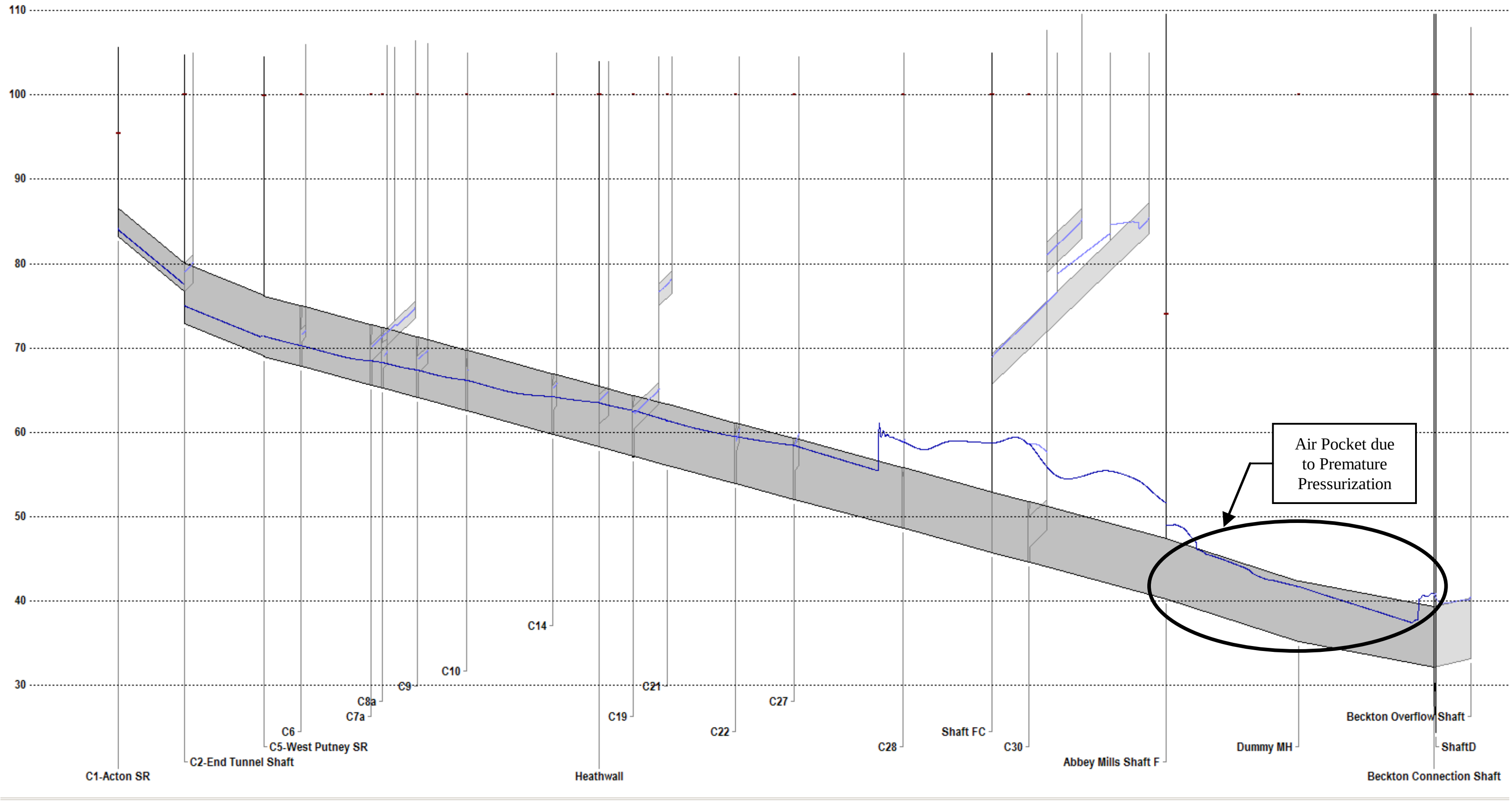
The transient and pneumatic performance of the Lee Tunnel (operating alone) and the complete tunnel systems were tested using output from a hydrologic/hydraulic model of the greater London collection system (large portions of which are Victorian brick sewers that are and will be continued in use). Most simulations were based on inflows produced from rainfall corresponding to a 15-year, 2-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. The simulated flows delivered to the tunnel system include both pumped flows and flows routed to the tunnels via collection tunnels and CSO consolidation structures. Parts of the existing collection system are capacity-limited, and events larger than this event are not expected to deliver significantly greater peak flows to the tunnels. In addition, a 5-year, 2-hour event and large historical storms were used to evaluate tunnel performance under less severe conditions.

Inflow hydrographs were produced by simulating the existing London collection system with various tunnel and collection tunnel alternatives. Within the hydraulic model, the tunnel system was linked to the existing system so that interaction between the existing system and tunnels and real time control of flows to the tunnel system could be simulated. An integrated system model was developed for selecting where CSO discharges would occur first and how often.. The hydrographs included flows delivered to over twenty inlets to the tunnel system, the exact number depended 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 majority of CSO discharges are pumped to the rivers as the existing collection system near the rivers is below mean tide levels. The relative ground elevation is a key consideration in determining critical water levels in the tunnel system as the value of land and adverse public opinion would preclude structures above ground level.

Results

Surge modeling 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. Premature pressurization, in which intermediate portions of the tunnel become surcharged before the most downstream section of tunnel surcharges, generally results from the cumulative effect of multiple inflow rates that, in sum, exceed the conveyance capacity of the tunnel. Surcharging of upstream tunnel sections in conjunction with bores moving upstream towards the surcharged upstream section can cause large pockets of air to become trapped in the tunnel, increasing the risk of geysering. An example of premature pressurization within the tunnel system is shown in Figure 11 (elevations shown are project datum which are 100 m above ordnance datum). Note the large air pocket that has formed at the lower end of the tunnel, due to surcharging in the vicinity of Abbey Mills Shaft F.

Figure 11 Lee and Thames Tunnel filling with Premature Pressurization



Recommended options for resolving these issues included restriction of peak inflows and total inflow volume to the tunnel, addition of storage and/or relief overflow points to reduce the magnitude of surges, and upsizing of the main Thames tunnel diameter. The first two options were investigated through a series of model runs using several tunnel layouts; upsizing of the tunnel was deemed impractical, primarily because of cost and potential for oversizing the tunnel system solely for transient conditions. This section presents a modification of one alternative, including both inflow controls and offline storage, sufficient to eliminate premature pressurization for both the 5-year and 15-year events, and to reduce peak HGLs to practical and implementable levels.

The first approach taken was to reduce the peak composite rate of inflow to the tunnel to prevent premature pressurization, since a moderation of peak inflow would reduce both the surges and the risk of geysers occurring within the system. Model simulations did not predict premature pressurization in the 2-year event. Based on this observation, controls of inflow were set at all locations to exclude sufficient volume over critical times during a 15-year event such that the total peak inflow was similar to the 2-year rates. Peak HGL levels within the Thames were restricted by collection system concerns and constructability issues at selected dropshafts, so inflow controls were amended to ensure that the final system HGL was below desired system elevations. There was confidence that a workable inflow control scheme could be implemented within the system, since much of the inflow was delivered to the system by pumping stations. Additional offline storage at selected shafts was sized to mitigate transient HGLs caused by the quickly filling tunnel. Another method used for controlling surge was to place overflow relief points at various locations, which has the effect of locally restricting the HGL to the level of the relief point. However, peak Thames River tide levels prevented this method from being used effectively while limiting HGLS below desired elevations. In addition, peak surge pressures at locations between relief points could still exceed the elevation of the points themselves, but these effects were minimized.

Figure 12 is a snapshot of the tunnel HGL during simulated filling with inflow controls in place, which shows that premature pressurization is avoided: a pipe-filling bore advances up the tunnel, but nowhere does the tunnel become surcharged before the bore arrives. For the most part, simulated peak HGLs are kept below critical elevations, with some exceptions occurring at the upstream ends of certain connection tunnels. Figure 12 also shows that the model predicts high HGLs in the smaller diameter portion of the tunnel at the upstream end of the Thames Tunnel between the Acton CSO connection tunnel and the upstream end of the main tunnel.

Figure 12 -- Lee and Thames Tideway Tunnel Mid-Filling, Showing Absence of Premature Pressurization during 15-Year Storm Event

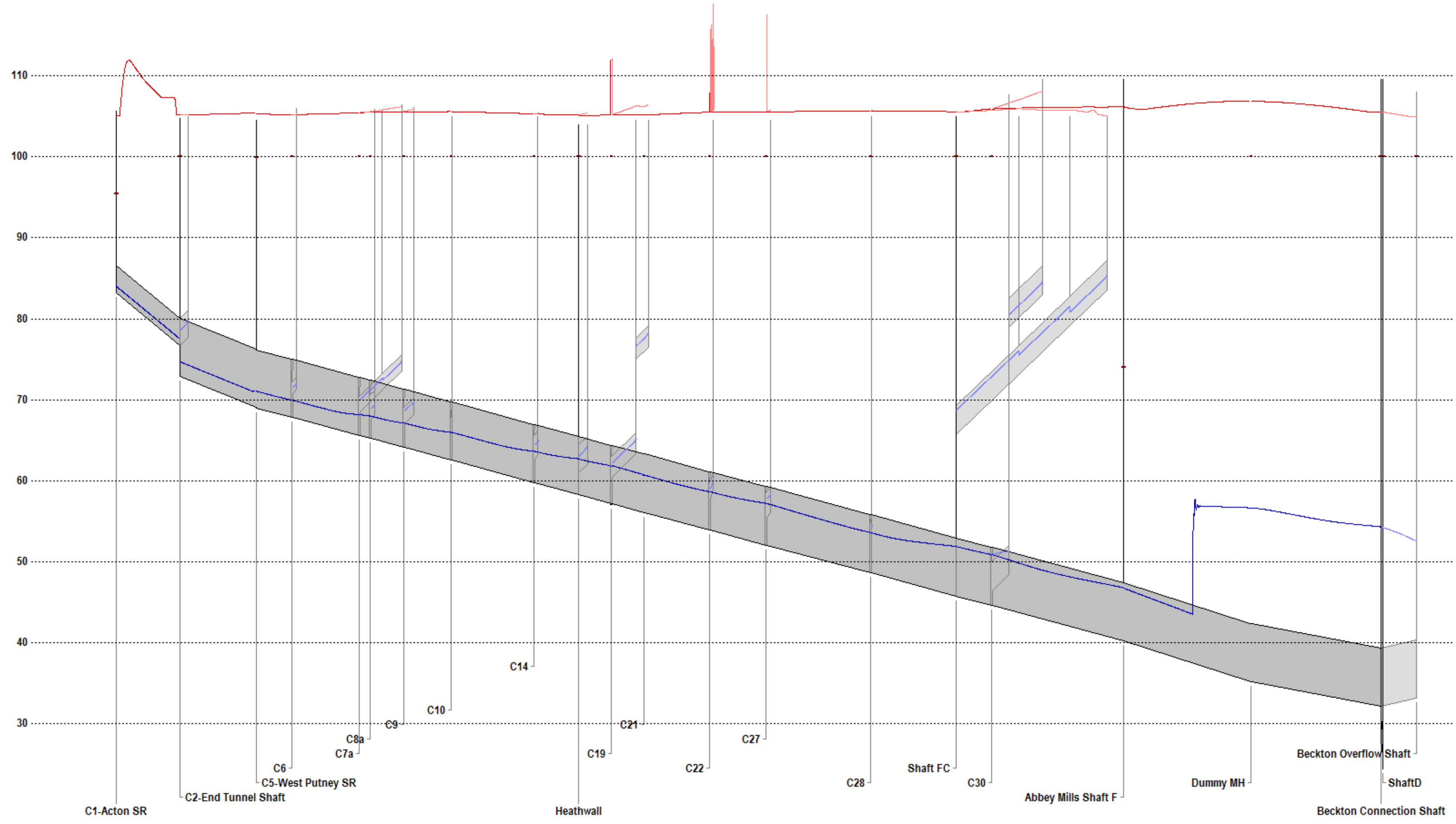


Figure 13 shows the predicted volumetric venting rates at selected shafts from a 15-year storm simulation with inflow controls. As air pressurization is not explicitly modeled in SHAFT, a simplified methodology for computing venting was employed, based on the reduction in volume available for air within each reach of the tunnel as it fills.. The peaks in venting rate are greater than 200 cms and generally occur along the main tunnel. The predicted peak inflow rates at each shaft rise to a peak rate in sequence, moving from downstream to upstream in the Thames Tunnel. These peak rates, which are associated with the movement of bores up the tunnel, are likely to be conservatively high, because it is assumed that all air moving ahead of the advancing bore is exhausted through the first shaft it encounters. In reality, high-rate air flows would be attenuated somewhat by a build-up of pressure, so that some of the air flow would be diverted to shafts located farther up-tunnel.

Figure 13 -- Venting Rate versus Time for the End Tunnel, Heathwall, Abbey Mills, Beckton Connection, Beckton Overflow, and West Putney Shafts

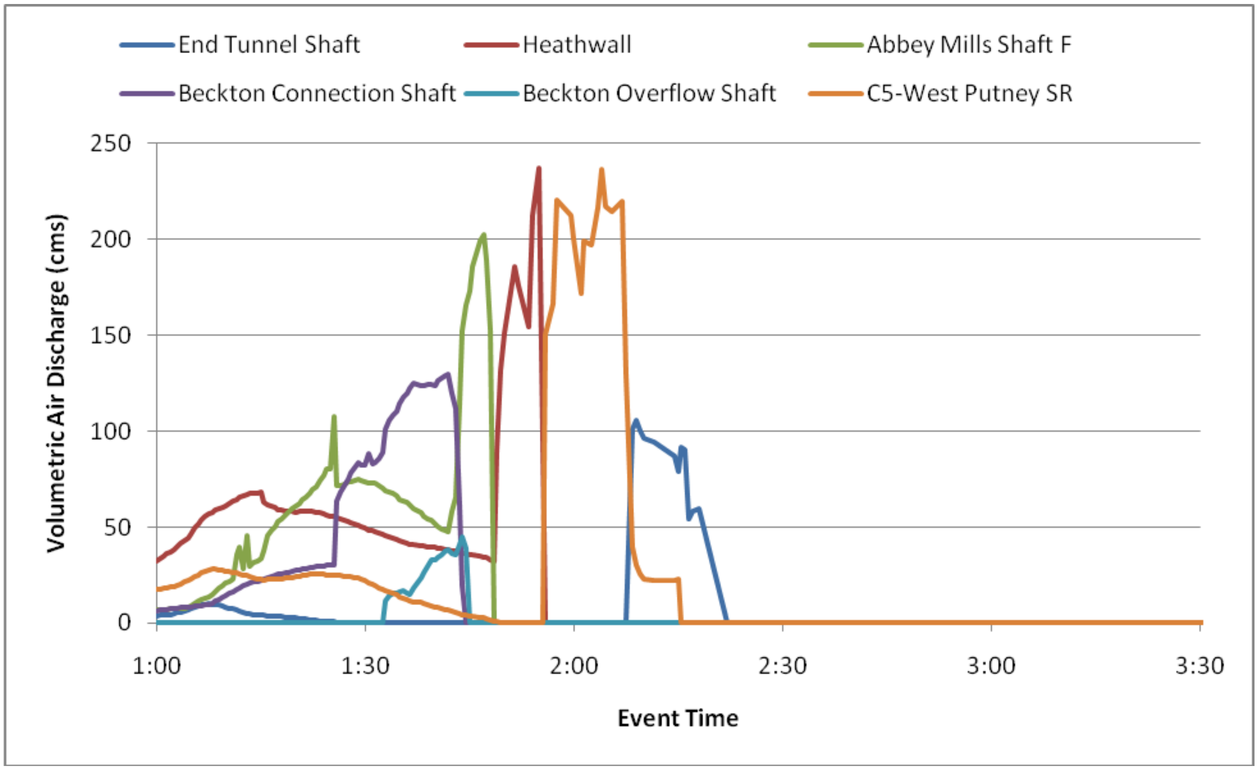
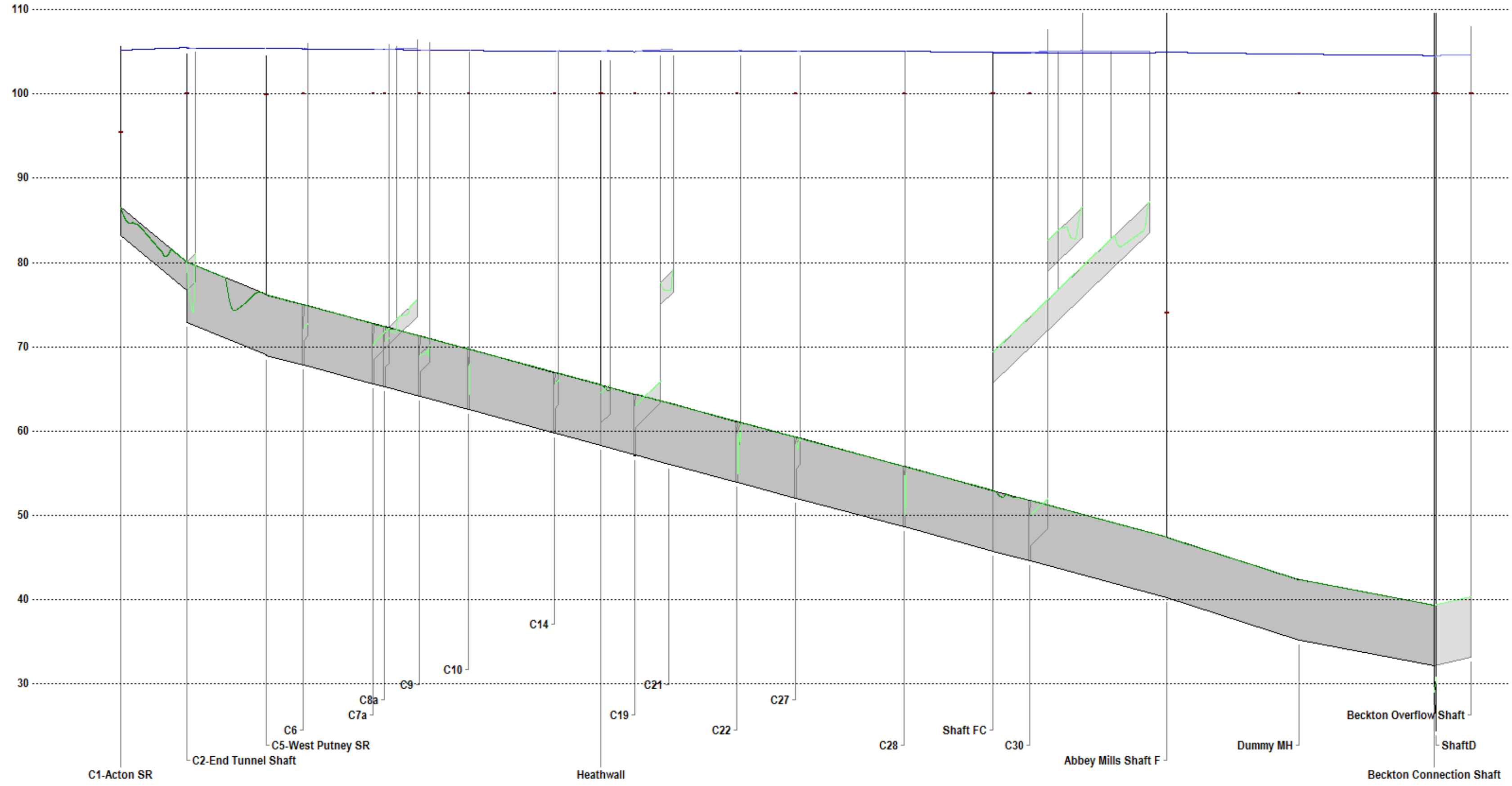


Figure 14 is a lower envelope showing the minimum gage pressure experienced at each London tunnels location. The greatest negative pressures are seen in upstream reaches of the main tunnel, and in certain connecting tunnels, where the model predicts the collapse of air pockets. The largest negative pressure predicted by SHAFT is approximately negative 3.5 meters at its most extreme point. Overall, the negative pressure resulting from surges is not a significant issue, with most reaches of the London tunnel experiencing no negative pressure.

Figure 14 -- Composite Picture of Minimum Gage Pressures in London Tunnels during 15-Year Storm Event



The London simulations reported above demonstrate the feasibility of the Lee and Thames Tideway Tunnels, with the inclusion of inflow controls and selected local offline storage. Inflow control and offline storage was essential in the simulations to minimize transient hydraulic grade line fluctuations. The addition of offline storage at the upstream end of the tunnel produced large reductions in peak HGLs in the complete system. Even with offline storage in place, however, inflow controls to the London tunnel are also essential to prevent premature pressurization and the formation of air pockets in the tunnel system. With inflow controls in place, the simulated maximum negative pressure due to air pocket collapse was acceptably low, and the probability of geyser formation was minimized.

CONCLUSIONS

The SHAFT model is a very useful computational tool for the evaluation and evaluation of alternatives to mitigate surges in large diameter tunnel systems. The SHAFT model's innovative approach for the calculation of PFBs, open channel bores, hydraulic transients and location of trapped air enables users to accurately determine potential problem areas in proposed or existing tunnel systems and evaluate solutions. The simulations performed for the DCWASA and London Tideway Tunnels systems have enabled designers to estimate peak and minimum HGLs, peak venting rates, and potential locations of large air pockets; they can also adapt their designs to minimize the effects of surges and trapped air. This analysis reduced the potential risk of failure of the proposed tunnel system under extreme events, and increased confidence that expensive retrofit solutions can be avoided.

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