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Surge predictions in a large stormwater tunnel system using SWMM

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ABSTRACT
Stormwater tunnels often have massive geometries, with conduits lengths of sev-eral kilometers and a wide range of diameter sizes. Modeling rapid filling of these systems is a complex task and needs adequate methodology. One model used in hydraulic analysis of stormwater tunnels is the EPA's Storm Water Management Model. However, model setup conditions related to pressurization algorithm can significantly impact SWMM's accuracy in surge prediction. This work evaluates SWMM 5.1 accuracy in simulating rapid filling of tunnels, particularly surging con-ditions. This evaluation is done using a real-world tunnel geometry, the Upper Des Plaines Tunnel (UDP), which is a part of Chicago's TARP tunnel system. Variables considered in SWMM model setup included discretization strategy, pressurization algorithm, and its results are compared with HAST predictions, a model specifically designed to represent surges in tunnels. This work shows that, with adequate setup, SWMM can represent surging in stormwater tunnels much more precisely.

KEYWORDS
Urban drainage; Preissmann slot; EXTRAN; Surging; Mixed flows

1. Introduction

Stormwater management in urbanized areas is a complex task, with goals of minimizing environmental impacts created by runoff discharges to receiving water bodies (Wanielista and Yousef 1992). These impacts are intensified in the case of combined sewer systems, when the collection systems carry simultaneously stormwater and wastewater. With dense urbanization, the availability of grade-level storage to mitigate these impacts to receiving water bodies is limited. Below-grade stormwater tunnels, sometimes spanning many kilometers, are an option being adopted in many areas (Wright et al. 2003). In addition to controlling environmental discharges of runoff to the environment, such systems also provide relief to the collection system, preventing episodes of local flooding. However, hydraulic transients are subject to occur within these systems and they may cause structural damages to the system (Li and McCorquodale 1999). Geysering, pressure surges, mixed flows, and blow-off of manhole covers are examples of the possible effects that could be caused by air entrapment or discontinuities in the conduit network (Cataño-Lopera et al. 2014).

Along these objectives, the Tunnel and Reservoir Plan (TARP) was created to protect Lake Michigan from pollution caused by combined stormwater and sewer overflows

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in Chicago area (MWRD 2020). According to the Metropolitan Water Reclamation of the District of the Greater Chicago MWRD (2020), the TARP sytem includes four tunnel systems named Upper Des Plaines, Des Plaines, Mainstream, and Calumet. These systems are located 45 to 90 m underground that result in 175 km of constructed tunnels, ranging from 2.5 to 10 m in diameter. Transient analysis involving 1-D and/or 3-D simulations were performed in the Calumet system (Leon et al. 2010) and in the North Branch of the Mainstream system (Cataño-Lopera et al. 2014). These studies evaluated different modeling efforts to represent the complex interaction of air and water in the tunnels. Those complex flows are also anticipated on the Upper Des Plaines (UDP) system. Accurate modeling of inflows within this system is needed to estimate surging processes within vertical structures.

A potential tool to perform this analysis is the EPA's Storm Water Management Model (SWMM 5.1), capable of a wide range of hydrologic and hydraulic analysis. Recent investigations have demonstrated improvements in SWMM 5.1 hydraulic accuracy with the addition of spatial discretization (Ridgway and Kumpula 2008; Vasconcelos et al. 2018; Pachaly et al. 2019) and the effects of using different pressurization algorithms and time steps (Pachaly et al. 2020b,a). Yet, these studies were performed in relatively simple geometries, not accounting for complex and multiple time-varying inflow hydrographs. Moreover, these studies did not involve comparing the accuracy of SWMM with models that were specifically built to represent surging in stormwater tunnels.

This work addresses this limitation by applying SWMM in the context of rapid filling of the TARP-UDP system during a realistic rapid filling scenario. A range of alternative setups to represent pressurized flows is considered, including a comparison between EXTRAN and the Preissmann slot, and different pressurized flow celerity values. Rapid filling and surging results from SWMM were compared to the Hydraulic Analysis of Sewers and Tunnels (HAST) model (Vasconcelos and Wright 2006), which has a robust hydraulic solver and was previously calibrated in portions of the TARP system.

2. Methods

2.1. *SWMM formulation*

The SWMM flow routing is solved using the Saint Venant equations (EPA 2020). These equations represent the 1-D unsteady free surface flows based on the conservation of mass (Eq. 1a) and linear momentum (Eq. 1b) (Sturm 2001). SWMM uses a network of links and nodes to compute the flow at each link and the head in each node (Rossman 2006; Roesner et al. 1988).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1a}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f + gAh_L = 0 \tag{1b}$$

where A denotes cross-sectional area; t denotes time; Q denotes flow rate; x denotes distance; H denotes the hydraulic head of water in the conduit; g denotes gravity;

h_L denotes the local energy loss per unit length of the conduit; and S_f denotes the friction slope, which is implemented with the Manning equation (Rossman 2006). More information on SWMM unsteady flow formulation, including its pressurization algorithms, can be found in Rossman (2006).

2.2. *HAST formulation*

The HAST model also uses the Saint Venant equations for solving pressurized and free surface flows. The model was used because its formulation was tested in a wide range of applications involving rapid inflows in closed conduits including large-scale stormwater systems (Vasconcelos and Wright, 2007, 2017). The model uses the Two-component Pressure Approach (TPA) (Vasconcelos and Wright 2006). The TPA represents the effects of pressurization in a single set of equations, starting from the set of mass and momentum equations in traditional pressurized pipe flows and assuming an elastic behavior to the pipe wall while neglecting water compressibility. This leads to the following set of equations:

$$\frac{\partial \vec{U}}{\partial t} + \frac{\partial \vec{F}}{\partial x} = S(\vec{U}) \tag{2a}$$

$$\vec{U} = \begin{bmatrix} A \\ Q \end{bmatrix} \; F(\vec{U}) = \begin{bmatrix} Q \\ \frac{Q^2}{A} + gAh_c + gAh_s \end{bmatrix} \; S(\vec{U}) = \begin{bmatrix} 0 \\ gA(S_o - S_f) \end{bmatrix} \tag{2b}$$

where h_c denotes the depth of the centroid of the cross-sectional flow area; and h_s denotes the pressure head associated with pressurized flows (positive or negative).

Equations 2a and 2b differ from the traditional Saint-Venant formulation because a surcharge head h_s is included. This term is zero if the pipeline flows in a free surface flow regime, and relates to the cross-sectional flow area A, the original pipe wall A_{pipe} and the acoustic wave speed a when the flow regime is pressurized. An advantage of HAST is that it was implemented using Roe's non-linear numerical scheme, as presented in Macchione and Morelli (2003), and shows little numerical diffusion for low Courant numbers. This is an important feature when modeling flow regime transition given that pressure wave celerity values can differ by up to 2 orders of magnitude.

2.3. *Geometry of TARP Upper Des Plaines*

The TARP Upper Des Plaines (UDP) system includes various dropshafts and tunnel reaches with diameters ranging from 1.5 m to 6.1 m, comprising a total length of approximately 13 km. Figure 1 presents a diagram of the UDP and some of its geometric features, including its junctions.

Typically when surging analysis is performed, it is desirable to account for a range of inflow hydrographs that are deemed representative for rapid inflow scenarios. However, this work focuses on a comparative analysis of SWMM 5.1 solution approaches to represent surges, thus a single inflow hydrograph was used for all tested conditions. This inflow hydrograph is shown in Figure 2, presenting its characteristics in different UDP dropshafts that were used in the SWMM and HAST simulations.

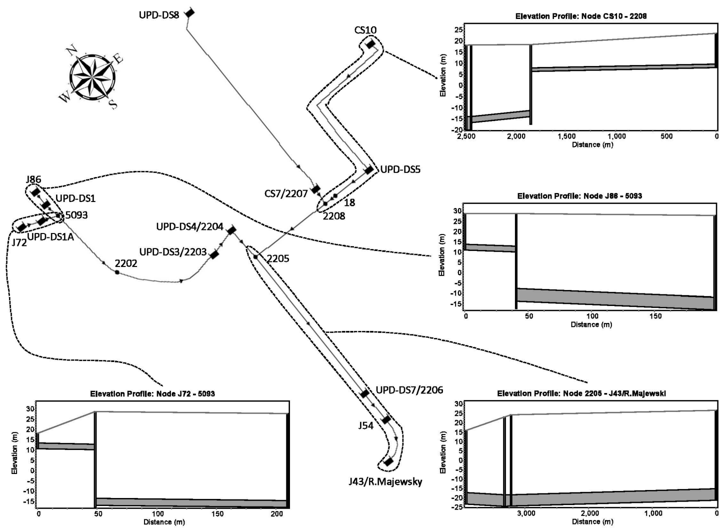

Figure 1. TARP Upper Des Plaines System schematic. Details in the figure show specific characteristics of the system: adverse slopes and drop shafts.

2.3.1. Numerical modeling variables

Recent investigations have indicated that SWMM modeling results are influenced by the choice of pressurization algorithm (Pachaly et al. 2020b,a), by using spatial discretization (Ridgway and Kumpula 2008; Vasconcelos et al. 2018; Pachaly et al. 2019) and also by the size of the time step (Pachaly et al. 2020b). These modeling setup variables were also selected in the present study in order to assess the accuracy of surge modeling accuracy in the context of stormwater tunnels.

One setup variable in this analysis is alternatives for SWMM flow pressurization algorithm. This work considered both the EXTRAN algorithm and four different alternatives of the SLOT algorithm. The first alternative was the SLOT as implemented in SWMM 5.1, is 1% of the pipe diameter and results in a pressure wave celerity in the range of 30 m/s for an unitary diameter. The SLOT implementation in SWMM includes the a modification proposed by Sjöberg (1982) whereby a gradual slot width change result in a smoother transition between free surface and pressurized celerity values. The second SLOT algorithm also has the 1% pipe diameter with but did not considered this gradual transition. The third and fourth SLOT algorithms applied a narrower slot developed by the authors that yielded a celerity of 250 m/s, either with or without the gradual slot transition. The rationale is that these larger wave celerity values are in the range of celerity values in pressurized flows with a small fraction of air. Altogether, 5 distinct pressurization algorithms were considered.

The second variable considered in this comparative study was the spatial discretizaton, and this was done by increasing the number of computational nodes in-between two consecutive structures (Ridgway and Kumpula 2008; Vasconcelos et al. 2018). As this option is not native in SWMM, the ReSWMM (Pachaly et al. 2018) tool was used. In addition to the traditional link-node approach, three discretization strategies were used splitting conduit reaches into smaller reaches of 20 (20 DxD), 10 (10 DxD), and 5 (5 DxD) times its own diameter.

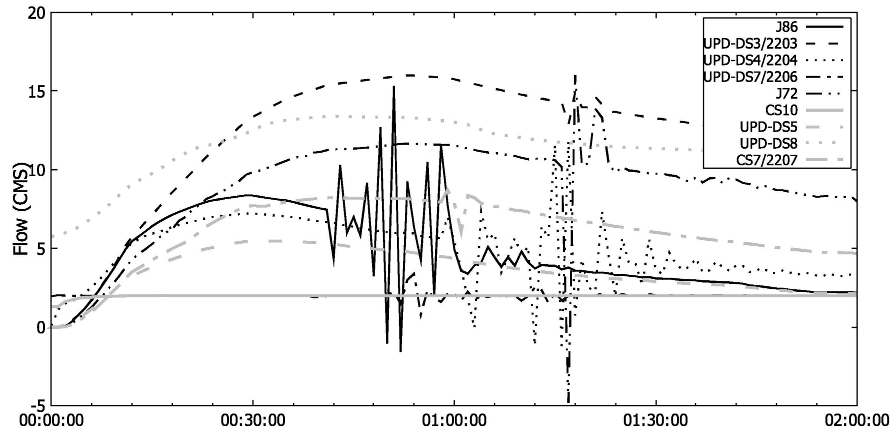

Figure 2. Inflow hydrographs in different UDP dropshafts.

Finally, the effect of time discretization was also considered. For the SLOT pressurization algorithm, it was used a range of values for Δt based on the Courant Condition (Eq. 3a). When the EXTRAN pressurization algorithm was used, the range of values for Δt followed the recommended routing time step proposed by Roesner et al. (1988), presented in equation Eq. 3b.

$$\Delta t = Cr\frac{L}{c} \qquad (3a) \qquad\qquad \Delta t \leq \frac{L}{\sqrt{gD}} \qquad (3b)$$

where Δt is the routing time-step; Cr is the Courant number; L is the smallest link length of the system; c is the wave celerity; and D is the link diameter. Figure 3 shows the simulations' summary that can be used as guide for readers. With a systematic variation of these parameters a total of 100 unique SWMM modeling setups are compared in the simulation of the TARP-UDP system, as is shown in Figure 3.

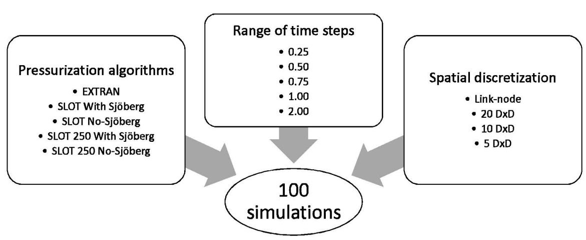

Figure 3. Simulations' summary

The TARP-UDP simulation performed with HAST used an acoustic wavespeed of 250 m/s, a discretization strategy where $\Delta x = D$, and a Courant number of 0.9. Facing the lack of observed field data and since the HAST modeling had as a key objective to understand possible causes and locations for observed geysering events, the calibration of HAST model was considered successful as it predicted the formation of large of large air pockets at the exact locations where it occurred within the TARP-UDP.

3. Results and discussion

3.1. *Numerical modeling continuity errors*

One of the most relevant outcome in a hydraulic simulation is to ensure small continuity error, at maximum in the order of few percent. With a high absolute continuity error, the model is not representing the flow as there is an incorrect storage or loss of water. We have postulated for the sake of comparison that results with continuity errors under than 1% as good, between 1% and 5% as acceptable, and larger than 5% as unacceptable. In comparison, continuity errors in HAST were under 0.2%. A summary of the continuity errors for all 100 SWMM simulations are presented in Table 1.

Table 1. Flow continuity error

Time Step Ratio	**0.25**	**0.5**	**0.75**	**1**	**2**
Spatial Discretization	**EXTRAN**				
Link-node	28.82	28.75	22.61	28.20	28.72
20 DxD	6.21	6.07	6.01	7.12	9.63
10 DxD	-0.02	3.24	4.99	6.74	16.03
5 DxD	-5.05	-4.08	3.41	5.69	15.46
	SLOT with Sjöberg				
Link-node	4.16	4.47	3.53	3.41	-7.20
20 DxD	2.12	1.78	1.38	2.18	2.76
10 DxD	1.80	2.12	2.28	2.03	-2.28
5 DxD	2.04	1.99	2.49	1.01	2.38
	SLOT No-Sjöberg				
Link-node	4.57	4.26	3.93	4.05	3.15
20 DxD	3.62	3.30	3.10	3.22	2.16
10 DxD	2.59	2.58	2.12	2.59	2.66
5 DxD	2.38	2.52	2.67	2.20	2.45
	SLOT 250 with Sjöberg				
Link-node	1.51	2.28	-1.42	3.40	2.96
20 DxD	4.22	3.96	3.78	3.81	3.62
10 DxD	3.55	3.38	3.13	2.86	2.48
5 DxD	3.10	2.70	2.92	3.02	3.17
	SLOT 250 No-Sjöberg				
Link-node	-1.00	0.24	4.04	-8.03	32.44
20 DxD	49.23	54.55	56.37	57.51	56.12
10 DxD	52.80	56.63	58.15	59.76	59.82
5 DxD	53.94	57.07	56.15	59.93	55.07

The vast majority of simulations had an absolute continuity error in the acceptable range of 1% and 5%. The worst continuity errors results were associated with the pressurization algorithms using the SLOT with 250 m/s and not using the gradual celerity transition by Sjöberg (1982). This was explained because in the simulations a hydraulic bore formed at the downstream end of the system junctions 2205 and J43/R.Majewski and pressurized the flow. Pressure oscillations at the pressurized side of the bore influenced the results negatively, consistently creating large continuity errors. Figure 4 illustrates this issue by presenting the water elevation profile predicted by HAST and different SWMM pressurization algorithms. The amplitude of pressure oscillations for the 250 m/s SLOT without gradual transition was the highest of the tested cases, including presenting unexpected large negative pressures. The representation by EXTRAN and the original SWMM slot algorithms, on the other hand, yielded hydraulic bore fronts with pronounced numerical diffusion, which in turn had an effect on surge prediction, as is discussed below.

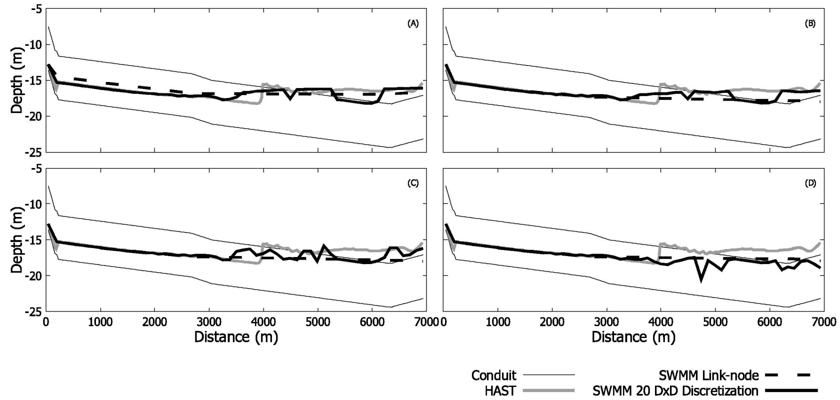

Figure 4. Profile at 3222s of simulation (Cr = 1) between UPD-DS1 and J43/R.Majewski: (A) EXTRAN; (B) SLOT; (C) SLOT 250m/s with Sjöberg transition; and (D) SLOT 250m/s without Sjöberg transition.

3.2. *Surge results*

Given the large number of tested conditions only the most relevant results are presented for the sake of brevity. Junction 2205 was selected to be evaluated because it is located in a key UDP location where different UDP reaches merge. Moreover, these results are representative of the surging predicted in other UDP junctions. Results with large continuity errors were not considered in the surge comparison as these are not representative of the flows. Therefore, solutions using the narrower SLOT with 250 m/s without gradual transition are omitted.

Comparing the SWMM results with the ones from the HAST model, EXTRAN pressurization algorithm was not able to properly capture the mass oscillations associated with surging after the pressurization of UDP reaches, as is shown in Figure 5. Peak surge was underestimated by more than 5 meters, and the oscillation period of surges was much larger. Spatial discretization improved results slightly, but in general these results are not representative of the anticipated surges. It is speculated that numerical diffusion of pressurization bores could be linked with this modeling outcome.

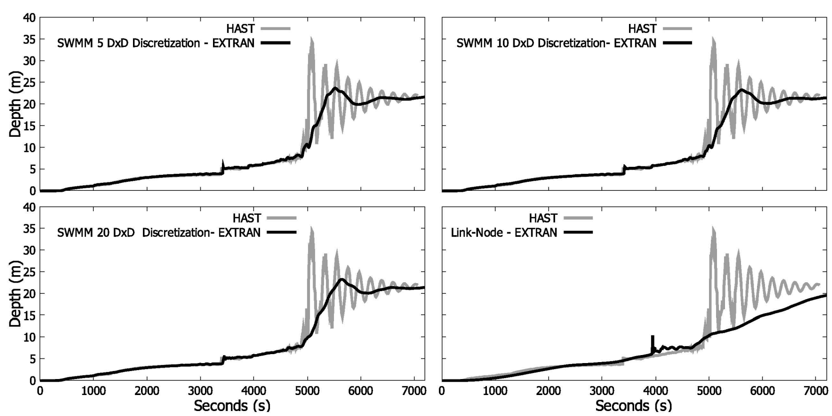

Figure 5. Surges predicted at Junction 2205 with EXTRAN algorithm using time step $\Delta t = L/\sqrt{gD}$

Results with the SLOT pressurization algorithm had a slight improvement in surging prediction when compared to the EXTRAN results as shown in Figure 6. However, the comparison with HAST results indicate that the peak surge is still underestimated and the frequency of surging is also not well represented. Similarly to the case of EXTRAN results, it is speculated that numerical diffusion and low acoustic wavespeed can be factors in the observed discrepancies in surging predicted by HAST and SWMM.

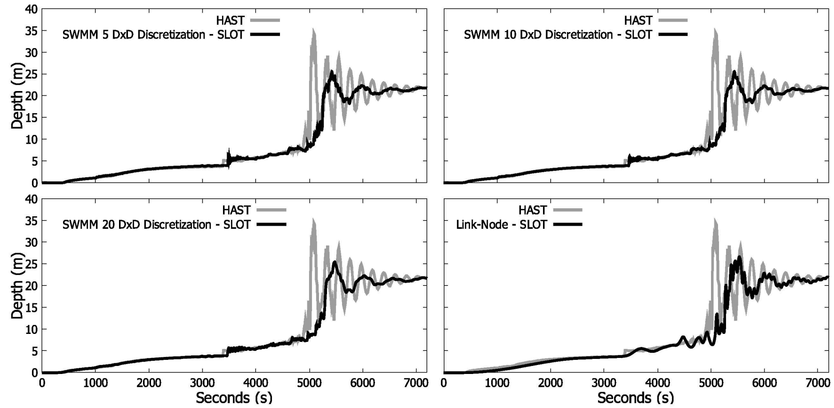

Figure 6. Surges predicted at Junction 2205 with SWMM's original SLOT algorithm using time step $\Delta t = 1.0(L/c)$

Surge predictions yielded by SWMM improved significantly when the narrower SLOT with 250 m/s celerity and Sjöberg slot transition was used. Although there was a slight delay in the initiation of surges, it can be noticed in the results presented in Figure 7 that the amplitude and the period of surges predicted by SWMM matched the results presented by HAST. With link-node discretization, however, spurious high-frequency oscillations were noticed in the surge results.

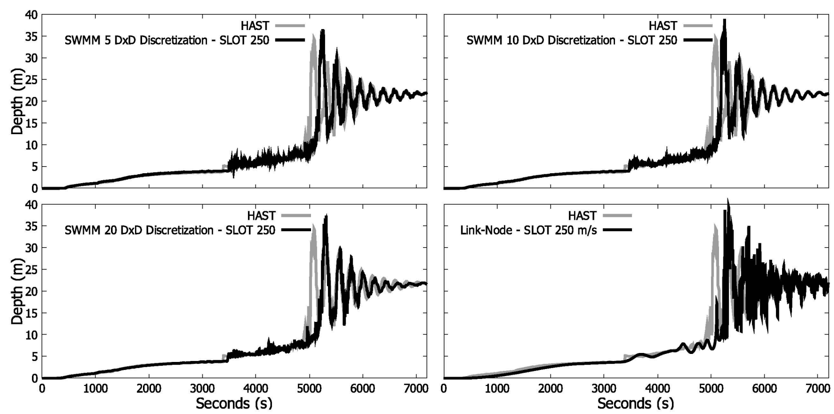

Figure 7. Surges predicted at Junction 2205 with the 250 m/s SLOT algorithm, Sjöberg gradual slot transition and time step $\Delta t = 1.0(L/c)$

Modeling runs with the SLOT algorithm and using other values of the Courant number indicated that SWMM can run simulations with Courant numbers exceeding 1. This is due to its iterative implicit procedure to update flows and head (Rossman 2017). However, the use of larger values of the Courant number occasionally created numerical instabilities, albeit resulted in smaller simulation times. On the other hand, using low values of the Courant number led to small-amplitude, high-frequency oscillations in surging results, in addition to longer computational times. Therefore, the recommendation for surge simulation using SWMM is to use spatial discretization, narrow SLOT algorithm (with Sjöberg transition) and a Courant number close to 1.0.

3.3. *Additional remarks in SWMM surging modeling setup*

As this investigation was performed, a problem was found in the cases when spatial discretization was used near junctions with discontinuous conduit invert elevations such as dropshafts. This problem was noticed through strong local numerical oscillation, that was also increasing continuity errors. A fix that was found for such issues was to artificially increase the slope of the last discretized reach at the upstream end of the drop. It is speculated that this change created a supercritical flows immediately prior to the drop, which is anticipated in real-world conditions. While in this investigation it was noticed that an offset of one diameter addressed these instabilities, this fix should be evaluated in a case-by-case basis. Figure 8 shows one instance where slopes were adjusted in the SWMM modeling of UDP.

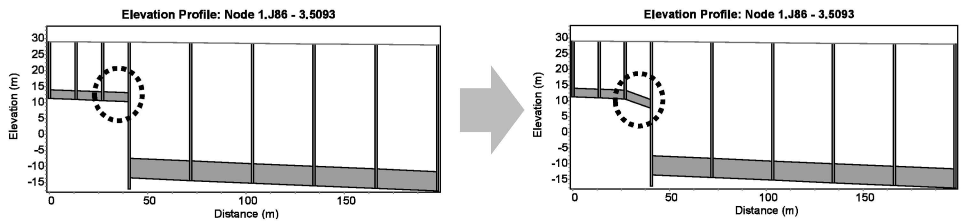

Figure 8. Slope Adjustment.

Another remark of using SWMM with spatial discretization for such large systems is the computational time spent to perform a single run. A simulation with the narrower SLOT algorithm can take few hours to be performed in a usual personal computer. However, the computational time by SWMM was still smaller than HAST model. This is possibly due to the finer spatial discretization used in HAST model.

A final point to be made is that SWMM is a single-phase (e.g. water) hydraulic model and thus neglect the effects of entrained/entrapped air phase during filling processes. In some cases such phenomenon is of fundamental importance to evaluate the likelihood of other relevant phenomena such as stormwater geysers, air-water surging and manhole cover displacements. If hydraulic modeling goals include represent air-water interactions during rapid filling in tunnels, other tools should be considered instead of SWMM.

4. Conclusions and recommendations

This work evaluated the applicability of SWMM to model surges in stormwater tunnels by comparing its results to another model that was specifically constructed to represent such flow conditions. Through the use of the narrow SLOT algorithm with gradual transition, spatial discretization, and Courant number of 1 it was noticed that predicted surges were very close in magnitude and frequency than the ones yielded by HAST model. This may indicate an interesting possibility to practitioners interested in hydraulic simulation of stormwater tunnels. In other conditions, SWMM predictions could yield significant continuity errors, misrepresentation of pressurization bores and surges of incorrect magnitude and frequency.

In the context of the rapid filling of the TARP UDP system, both pressurization algorithms originally implemented in SWMM underestimated the water peak level in the shafts and yielded much larger surge oscillation periods. Another finding of this work was the importance of the Sjöberg (1982) slot transition in improving the stability of bore propagation predictions. Particularly for the narrow slot alternative, the gradual slot transition enabled the decrease of continuity errors during the simulation of hydraulic jump propagation. Other sources of instabilities linked to the discontinuity of conduit inverts were also noticed in the study; a fix based on increasing the conduit slope immediately upstream from the drop addressed this issue. A final observation was that SWMM simulations using pressurization algorithms based on the Preissmann slot can have the time step decision based on the Courant condition. While SWMM could handle simulations with Courant number deviating from unity, best results were achieved with Courant number close to unity.

It is hoped that this finding will help practitioners in setting up SWMM models to represent with better accuracy the surging processes in stormwater tunnels. Since SWMM is one of the most popular stormwater models worldwide that has many different boundary conditions and it is an open-source software, increasing its applicability to surge prediction can facilitate the modeling of stormwater systems by avoiding the usage of other models for surge prediction that are often not free-to-use software. However, one disadvantage is the inability of SWMM to consider air phase effects in the simulation of rapid filling tunnels and related surging. Tools that incorporate this aspect should be used if these interactions are anticipated in stormwater systems undergoing rapid filling.

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