Investigation of rapid filling of poorly ventilated stormwater storage tunnels

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ABSTRACT

Below-grade stormwater storage tunnels are designed to provide relief for collection networks during intense rain events. Air must be evacuated as the tunnel fills and, depending on the system geometry, the air may become pressurized. This research presents an investigation on various ways that the air pressurization influences the water flow. The investigation used an experimental apparatus consisting of a horizontal 14.8 m long, 94 mm diameter acrylic pipeline with various degrees of air ventilation. The experiments were primarily conducted to explore two features of the flow termed pre-bore motion and the interface breakdown. Experimental measurements include flow velocity, air and water pressure, and flow depth. The experimental results were compared to the predictions of a numerical model based on the Saint-Venant equations that handles the flow regime transition and the possibility of air pressurization. The numerical predictions agree well with the experimental observations and provide an explanation for the interface breakdown occurrence.

Keywords: Air pressurization, Experimental investigations, Flow regime transition, Numerical Models, Stormwater

1. Introduction

Due to water quality considerations, increasingly stricter regulations controlling combined sewage and stormwater releases to the environment have been enacted in recent years. The construction of storage facilities is a typical approach to meet regulatory requirements for the control of these flows. Below-grade storage tunnels may be a preferred alternative in order to simultaneously provide storage at a number of separate overflow points. Operational problems in several systems have resulted in investigations into the nature of the flow in such tunnels. Geysering events related to surcharging in stormwater tunnels were reported by Guo and Song (1990, 1991) in the Chicago Tunnel and Reservoir Project (TARP) system as well as other systems. Severe pressure transients experienced in a 3 m diameter trunk sewer in the city of Hamilton, Ontario, were strong enough to blow off welded manhole covers on a drop shaft (Li and McCorquodale 1999). Zhou et al. (2002b) reported structural damage in
the stormwater system of Edmonton, Alberta, during a high intensity rain event, in which the sewers experienced surcharging and flow regime transition. Pressurization of the air phase displaced from tunnels during rapid filling events may be a key factor in the development of these undesirable conditions.

Several previous studies consider interactions between air and water in a rapidly filling pipeline. These include both numerical and experimental studies. However, due to various limitations of either the experimental configuration or the numerical technique applied, it is difficult to make definitive statements on the role of the air on system behavior. It would be helpful to understand what interactions between air and water are possible during a rapid filling event and the required capability of a numerical model to describe these interactions. The purpose of this work is to report on a more detailed investigation of qualitative observations reported previously by Vasconcelos and Wright (2005). By providing a more complete description of various phenomena, it is demonstrated that air pressurization in a poorly ventilated pipeline can have a significant influence on the dynamics of an underlying free surface flow. A critical issue is that this influence can result in the entrapment of discrete air pockets in the pressurized pipe and these air pockets may have detrimental effects on system response. In order to capture the effects of air pressurization in a numerical model, a fully dynamic free surface model was coupled to an analysis of the air pressurization.

A majority of previous investigations on rapid filling of stormwater systems are related to the development of numerical models to simulate the filling events. Hamam and McCorquodale (1982), Li and McCorquodale (1999), Aimable and Zech (2003) and Savary et al. (2003) conducted experimental and numerical investigations of rapid filling of conduits in which discrete air pockets were formed. Air pocket formation was assumed to be created by shear-flow instabilities generated by the relative motion between the air and water phases in near-horizontal pipes undergoing flow regime transition. Air pockets move within the pressurized zone and are eventually expelled at venting points, potentially causing sharp pressure spikes and/or geysering.

Using an approach based on the Preissmann scheme to model the flow regime transition, Nguyen (1999) proposed a numerical model to simulate the flow in a conduit in the presence of a pressurized air cushion. In this model the Saint-Venant equations are solved assuming that the piezometric head is composed of the flow depth and either the surcharge head or the air pressure head. While the model applies the same numerical scheme throughout the domain, the approach is limited by not providing a methodology that automatically relates flow area and surcharge pressure, such as the Preissmann slot concept. This resulted in a convoluted approach that somewhat nullified the benefits of using a single set of equations. Arai and Yamamoto (2003) proposed a model that used the Preissmann slot concept
(Cunge and Wegner 1964) and solved the mass and momentum equations for both the water and air phases. The equations were solved in an implicit fashion, using the four-point Preissmann scheme. An experimental apparatus was used to calibrate and verify the model. Shear forces between the phases are included in the model; however the generation of air pockets due to this mechanism was not reported. Even though the flow was suddenly introduced over initially still water conditions in the experiments, no bore formation was reported although it would be expected (Henderson 1966, Toro 2001).

Zhou et al. (2002a,b) presented an experimental and numerical investigation on the description of the rapid filling of an empty horizontal pipe with limited ventilation. The main goal of the investigation was to predict the peak pressure as water flow was suddenly admitted into the system and expelled the air phase initially present in the pipe. Similar to the approach proposed by Martin (1976), the numerical model was constructed using a lumped inertia approach, assuming a vertical interface separating the advancing water front and the air that initially filled the pipe and describing the air escape through an orifice at the downstream pipe end with a simple head-discharge relationship. While the model was generally successful in predicting the experimental results, the concept of a vertical interface from empty to full pipe states to characterize a flow regime transition event is not expected to be appropriate in stormwater applications due to the typical filling scenarios in such systems.

A systematic investigation on the interaction between the air and water phases was conducted by Vasconcelos and Wright (2005). In this investigation, water was suddenly introduced through an inflow box connected to one end of an initially stagnant, partially-filled pipeline with a surge riser at the opposite end. Different inflow discharges, pipeline slopes and initial water levels were investigated and observations were made to determine flow behavior that numerical models would need to be capable of resolving. Various air-water flow interactions were reported, and generally those interactions resulted in significant changes in the behavior of the water flow. One of the observed flow features was referred to as *pre-bore motion* (PBM), characterized by water motion in the free surface portion of the flow far ahead of the pipe-filling bore created by the flow initiation. It was established that the pre-bore motion was generated by pressurization of the air phase above the initially stagnant water surface. The air pressurization initiated flow from the pipe into the downstream surge tank and a depression wave was generated that propagated upstream. Another flow feature of importance was *interface breakdown* (IBD), in which a pipe-filling bore front would experience an air intrusion at the pipe crown. Further experiments performed by Vasconcelos and Wright (2006) have demonstrated that this previously unreported mechanism may lead to air pocket entrapment in pipelines, which in turn is a potential source for the previously discussed operational problems in stormwater storage tunnels.

The present investigation was motivated by these previous observations. The determination that
these types of interactions between air and water were possible indicated that certain types of numerical models would be incapable of resolving the observed phenomena. The general modeling requirements led to the model development described in Vasconcelos, et al. (2006). However, the original experiments did not involve quantitative measurements that would be necessary to rigorously assess the ability of any numerical model to describe the relevant phenomena. An additional experimental investigation was conducted in order to resolve the flow phenomena in more detail and to provide experimental measurements that can be used to evaluate numerical models.

2. Objectives and methodology

The results of a more detailed investigation related to two of the flow features resulting from the interactions between air and water phases during the rapid filling of poorly ventilated stormwater systems described by Vasconcelos and Wright (2005) are provided. These flow features are the pre-bore motion and the interface breakdown, shown schematically in Fig. 1. The investigation included measurements of flow velocity, water depth and pressure variations during these phenomena. This work was coupled with the development of a numerical model able to reproduce these flow features using a shock-capturing scheme to solve the Saint-Venant equations including the additional effect of the air phase pressurization.

![Figure 1 Sketches of (a) Pre-bore motion and (b) Interface breakdown flow features](image)

The experimental apparatus consisted of a horizontal 14.8 m long, 94 mm diameter acrylic pipeline as shown in Fig. 2. The initial state was established by partially filling the pipe and allowing the water to become stagnant. The experiments were performed by initiating a sudden inflow by means of a two-way valve into the apparatus through a 0.25 m ×0.25 m acrylic fill box with a spill level 0.15 m above the pipe crown. A surge tank with a diameter of 0.19 m was installed at the downstream end.
An important component of these experiments was to control the air release which was allowed only through a 0.0254 m diameter ventilation tower placed at the pipeline end, adjacent to the surge tank. Air escape through the upstream end of the pipeline was prevented by choosing a combination of initial water depth and inflow rate that resulted in the immediate formation of a pipe-filling bore upon flow admission into the fill box. Air escape through the surge tank was prevented by an acrylic gate that was located at the surge tank end and projected below the initial water surface. Flow conditions were selected to prevent air from escaping beneath the gate. The only ventilation in the system was through the ventilation tower; rounded nozzles of different diameters were installed at its top to restrict the air flow. This provided a means by which the air pressure within the system was directly related to the rate of air escape through the venting tower by an orifice equation.

Initially, it was unclear what parameters should be measured to quantify IBD events since it was not understood what events led to its occurrence. A number of preliminary experiments were performed that are not included herein but are reported in Vasconcelos (2005). An initial question was whether the IBD was triggered by changes in the flow conditions that occurred at the system boundaries during the filling event. There were two potential boundary effects identified; when the upstream fill box started to spill and when the surge tank water level reached a stable level after the initial rise due to the air pressurization. The preliminary experiments demonstrated that there was no connection between IBD and the timing of these events at the system boundaries. Therefore, it was concluded that the conditions near the pipe-filling bore front must be important in the initiation of the process. An additional observation in some of these preliminary experiments was that the IBD was eliminated a short time after formation and the pipe-filling bore front re-formed.

The following non-dimensional (starred) variables are defined to present the results
\[ x^* = \frac{x}{L} \quad t^* = \frac{t}{L/(gD)^{1/2}} \quad H^* = \frac{H}{D} \quad h^* = \frac{h}{D} \]

\[ V^* = V / (gD)^{1/2} \quad Q_{i}^* = Q_{i} / (gD^5)^{1/2} \quad d_{orif}^* = \frac{d_{orif}}{D} \quad h_{air}^* = \frac{h_{air}}{D} \]

(1)

in which \( L \) and \( D \) are the pipeline length and diameter, \( x \) is the streamwise pipeline coordinate measured from the upstream end, \( t \) is time, \( g \) is the gravity acceleration, \( H \) is the overall piezometric head (including air phase pressure head), \( h \) is the water depth, \( V \) is flow velocity, \( Q_{i} \) is the water inflow discharge, \( d_{orif} \) is the diameter of the air ventilation nozzle, and \( h_{air} \) is the air phase pressure head.

In the experiments reported, the measurements involved the following instruments:

- Digital video camera recording at 30 frames/s with a ruler located at \( x^* = 0.953 \);
- Three Endevco® piezo-resistive pressure transducers, model 8510B-1 (1 psig), located at the top and invert of \( x^* = 0.953 \), and at the invert of \( x^* = 0.649 \);
- Data acquisition system of National Instruments® model DAQ-Pad MIO-16XE-50; and
- Acoustic Doppler Velocimeter (MicroADV) of Sontek®, located at \( x^* = 0.649 \).

The procedure for the experiments was as follows:

1. Establish stagnant conditions in the pipe with a desired initial water level;
2. With the two-way valve adjusted to discharge outside the fill box, the desired discharge was initiated and allowed to become steady;
3. The two-way valve was then rapidly switched so that the discharge was admitted into the fill box; and
4. As the resulting bore front advanced in the pipeline, the measurements were performed.

The video recorder and ruler were used to measure the water depth variation during the inflow events. The data collection extended to 300 s \( (t^* = 19.5) \), which generally corresponded to the time required for the oscillations in the surge tank water level to become negligible. At that point, it was assumed that the whole system was under a constant pressure head and the transducers were calibrated assuming a linear relationship between the difference in the initial and final transducer outputs and the difference between the initial water level and final pressure head in the system defined by the level in the surge riser.

The range of experimental variables considered herein is listed in Table 1. Experiments were also conducted with a ventilation nozzle with \( d_{orif}^* = 0.135 \); no signs of air pressurization were detected for this nozzle size. Eight experimental conditions which led to air pressurization are presented below. All were repeated three times to ensure consistency of the results. This was motivated by the manual startup of the inflow and the measurement devices, which could result in minor discrepancies in the
timing and other details of the measurements. This procedure also helped to detect measurement problems. One of these problems sometimes occurred during the passage of the pressurization front past the transducer at the pipe crown. Small air bubbles could remain attached to the transducer and affect the pressure readings. Another measurement problem was caused by the attachment of air bubbles to the MicroADV probe as the pipe-filling bore swept over that location. Although the experiments were repeated to ensure consistent results, only one representative measurement is presented below.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Range of Values</th>
</tr>
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<tbody>
<tr>
<td>(h_i^*)</td>
<td>0.76 and 0.81</td>
</tr>
<tr>
<td>(Q_i^*)</td>
<td>0.365 and 0.460</td>
</tr>
<tr>
<td>(d_{orif}^*)</td>
<td>0.101 for PBM and 0.068 for IBD experiments</td>
</tr>
</tbody>
</table>

3. Experimental results

The complete set of experimental results (involving additional measurements for the presented experiments as well as other experiments) is reported in Vasconcelos (2005); only representative results are presented herein. The \(H^*\) variation at the invert of \(x^* = 0.953\) and the depth variation at the same location were selected to demonstrate the effects of the experimental variables in the filling process.

Figure 3 shows the \(H^*\) variation for the four experimental conditions in which the larger ventilation nozzle with \(d_{orif}^* = 0.101\) was used. Notice the increase in pressure head immediately after the flow is initiated. Since the pipe-filling bore front could not reach \(x^* = 0.953\) so rapidly, this is a result of air pressurization, as confirmed by the pressure measurements obtained at the pipe crown at the same location (results not shown). Generally, there is a steady growth of the pressure head as the inflow front approaches the downstream end of the pipeline, and the maximum pressure increases with the inflow discharge. This is expected, as a discharge increase leads to a larger air outflow through the nozzle requiring a larger air pressure if an orifice-type discharge condition is considered.

The pressure spike followed by the rapid increase in \(H^*\) corresponds to the interaction of the hydraulic bore with the gate blocking the air outflow through the downstream end. As the inflow front reaches the downstream end, essentially no air remained in the pipeline. The inertial oscillations that followed had slightly different magnitudes among the different inflow discharges tested, with larger pressure heads recorded for the larger inflow discharge. The initial \(H^*\), which equals \(h_i^*\) within the pipeline, did not alter the magnitudes of the inertial oscillation. However, as expected, the arrival time of the inflow front was sooner for larger initial water depths as the inflow bore propagates faster in
these cases.

Figure 3 Pressure head variation $H^*\!(t^*)$ for the four cases with $d_{orif}^*=0.101$, at $x^*=0.953$. (a) $h_i^*=0.76$, $Q_i^*=0.365$; (b) $h_i^*=0.81$, $Q_i^*=0.365$; (c) $h_i^*=0.76$, $Q_i^*=0.460$; (d) $h_i^*=0.81$, $Q_i^*=0.460$

This pressure head variation has the same overall behavior for the experiments conducted with the smaller ventilation nozzle of $d_{orif}^*=0.068$, shown in Fig. 4. Two observed differences compared to the larger ventilation nozzles is that a greater increase in air pressure head occurs as the inflow front advances and there is a longer time required for the inflow bore to arrive at the measurement location. This is linked with the air cushioning effect of the pressurized air phase, which retards the advance of the bore. The inertial oscillation pressure peaks varied slightly between the four studied conditions. One important distinction between these experiments and those performed with the larger ventilation nozzle is that IBD was observed in these conditions. For the condition with $h_i^*=0.76$ and $Q_i^*=0.365$, the open-channel bore front evolved into a new pipe-filling bore front after IBD was observed, and advanced towards the downstream end of the pipe, entrapping a long and thin air pocket behind it.
The $h^*$ variation for the same flow conditions are shown in Figs. 5 and 6. The flow depth varied more with the larger inflow discharge as a consequence of the larger air pressure, resulting in a more pronounced pre-bore motion. Generally, a sudden drop in depth $h^*$ of the order of 0.1 (corresponding to 0.011 m) was observed. A gradual depth recovery follows, and in some cases the depth nearly returned to its initial value. The sudden jump in the depth is observed with the arrival of the inflow front.

The same general pattern was observed when the experiments were conducted with the smaller ventilation nozzle. However, as shown in Fig. 6, the depth recovery that followed the sudden initial drop was much less pronounced, which is an indication of greater air pressurization. The case in which the IBD was followed by the redevelopment of the pipe-filling bore front ($h_i^*=0.76$ and $Q_i^*=0.365$) was the one in which the depth variation was smallest ($\Delta h^*=0.08$ or 0.09). The air cushioning effect caused by the greater air pressurization delayed the arrival of the inflow front.
Figure 5 Water depth variation $h^*(t^*)$ for the four cases with $d_{orif}^*=0.101$. (a) $h_i^*=0.76$, $Q_i^*=0.365$; (b) $h_i^*=0.81$, $Q_i^*=0.365$; (c) $h_i^*=0.76$, $Q_i^*=0.460$; (d) $h_i^*=0.81$, $Q_i^*=0.460$

Figure 6 Water depth variation $h^*(t^*)$ for the four cases with $d_{orif}^*=0.068$. (a) $h_i^*=0.76$, $Q_i^*=0.365$; (b) $h_i^*=0.81$, $Q_i^*=0.365$; (c) $h_i^*=0.76$, $Q_i^*=0.460$; (d) $h_i^*=0.81$, $Q_i^*=0.460$

4. Numerical modeling of rapid pipe filling with air-water interactions

4.1 Model description

A finite-volume-based numerical model for the rapid pipeline filling problem is proposed based on a modified version of the Saint-Venant equations. The equations are solved with a non-linear, shock-capturing scheme capable of resolving possible flow discontinuities (hydraulic bores) that may appear spontaneously in the solution. This approach has been applied by a number of investigators, including Glaister (1988), Garcia-Navarro and Saviron (1992) and Toro (2001). In stormwater storage tunnels,
the possibility of transition to a pressurized flow regime adds to the complexity of the problem as the original form of the Saint-Venant equations do not hold for pressurized flow regimes. In such a case, a conceptual model such as the Preissmann slot (Cunge and Wegner 1964) or the newer Two-component Pressure Approach (Vasconcelos et al. 2006) is capable of extending the original models to allow for the flow description in the pressurized flow mode. The Two-component Pressure Approach (TPA) was applied to assess the behavior of this approach in a scenario in which air pressurization is considered in the equations. The pipe elasticity was adjusted to yield an acoustic wave speed of 50 m/s, which is on the order of the values found in literature for Preissmann slot-based models (Capart et al. 1997, Trajkovic et al. 1999). This value also helps in diminishing the effect of post-shock oscillations that appear in the simulations, as described by Vasconcelos et al. (2006).

The Saint-Venant equations modified to allow for the inclusion of the air phase pressurization can be expressed in a conservative form as:

\[
\begin{align*}
\dot{U} + \dot{F} &= S \\
\dot{U} &= \begin{bmatrix} A \\ Q \end{bmatrix} \\
S(\dot{U}) &= \begin{bmatrix} 0 \\ gA(S_o - S_f) \end{bmatrix}
\end{align*}
\]

if \( A < A_{pipe} \Rightarrow \dot{F} = \begin{bmatrix} Q \\ \frac{Q^2}{A} + gA(h_c + h_s) + gA_{pipe}h_{air} \end{bmatrix} \) 

if \( A \geq A_{pipe} \Rightarrow \dot{F} = \begin{bmatrix} Q \\ \frac{Q^2}{A} + gA(h_c + h_s) \end{bmatrix} \) 

(2)

in which \( \dot{U} \) is the vector of conserved variables, \( \dot{F} \) is the vector of conserved variable fluxes, \( S \) is the vector of source terms, \( A \) is cross-sectional area of water, \( Q \) is discharge, \( A_{pipe} \) is cross-sectional area of the pipe, \( h_c \) the distance between the free surface and the centroid of the water cross-sectional area, \( h_s \) the surcharge head calculated with the TPA approach, \( S_o \) is the bed slope and \( S_f \) is energy slope given by the Manning equation herein. The inclusion of the air phase term is similar to the approach used by Arai and Yamamoto (2003). Their method differs mainly in the numerical scheme as they implemented a linear, implicit Preissmann scheme (Abbott 1979). A non-linear shock-capturing scheme based on the approximate Riemann solver proposed by Roe (1981) was adopted to improve the bore simulation accuracy. The implementation of the Roe scheme here follows closely what was presented by Macchione and Morelli (2003). Note that the additional term \((gA_{pipe}h_{air})\) effectively acts only at the pressurization front interface where the air phase pressure exerts a cushioning effect as the pipe filling bore advances in the pipeline.

The air phase flow is formulated assuming that it is not choked through the ventilation nozzle. Following Zhou et al. (2002b), the relationship between air pressure and outflow discharge in such
conditions is

\[ Q_{\text{air}} = C_d A_{\text{orif}} Y \sqrt{2g \frac{\rho_w}{\rho_a} h_{\text{air}}} \]  

(3)

in which \( Q_{\text{air}} \) is air discharge, \( C_d \) is the air outlet discharge coefficient, \( h_{\text{air}} \) the gage air pressure head, \( Y \) is an expansion factor (a function of \( h_{\text{air}} \) and the polytropic coefficient), and \( \rho_a \) and \( \rho_w \) are the densities of the air and water phases, respectively. By applying continuity of the air phase, and using Eq. (3) to relate \( Q_{\text{air}} \) and \( h_{\text{air}} \), the following relation is derived for the air pressure head

\[ h_{\text{air}} = \frac{1}{2g \rho_a} \frac{\rho_a}{\rho_w} \left[ V_s (A_{\text{pipe}} - A_{fs}) \right]^2 \]  

(4)

in which \( V_s \) is the pipe-filling bore front velocity and \( A_{fs} \) is the cross-sectional area of the free-surface flow portion. The possibility of choking at the nozzle was not considered as the air pressures were sufficiently small to avoid this occurrence. Although the method accounts for changes in the air density, it was found that in the ranges of the experiments conducted, such a variation was always insignificant. Accordingly, the value of the variable \( Y \) was always essentially unity. The value adopted for the round nozzle discharge coefficient was \( C_d = 0.98 \).

It is acknowledged that this simple treatment of the air phase can only be justified in the simulation of a problem performed at a laboratory scale. The hypothesis of a constant value for \( h_{\text{air}} \) throughout the pipeline can be shown to not impact the simulation of the experiments due to the relatively short pipeline length. In actual systems, in particular with greater length, a more precise formulation for the air phase is required since the air pressure within the pipe is likely to have some spatial variation if there are long distances between the ventilation points. Simulation of larger scale problems would require adaptations to the air phase modeling equations to allow for spatial variations of the air pressure due to shear forces; Eq. (2) is structured to handle such air pressure variations.

It is also acknowledged that a limitation of this approach is that it cannot handle the entrapment of air pockets within the pressurized flow portion. This is due to the intrinsic inability of the Saint-Venant equations to model air pockets entrapped within the flow. At the leading edge of these pockets the free surface curvature is strong, and thus the vertical accelerations, neglected in the development of the Saint-Venant equations, become significant. The Saint-Venant equations cannot strictly be applied to simulate flows with the presence of air pockets. Other model approaches, such as those based on rigid column approaches, introduces simplifying hypothesis for the air pocket modeling, such as uniform air thickness over the pocket, which are not totally justified. The issue of air pocket modeling and air motion in pressurized flows remains a challenge to transient, one-dimensional models for the
simulation of rapid filling in closed conduits.

Regarding the boundary conditions of the model, there are three variables to be solved at each of the pipeline ends, namely the water level at the inflow box and the riser as well as flow area and discharge at the immediately neighboring cells. To solve for these variables, three equations are also applied: mass and momentum conservation and the appropriate characteristic equation.

4.2 Model results

As the subsequent results indicate, the proposed model was able to successfully predict the effects of the air phase pressurization, the pressure head variations and the observed changes in depth and velocity during the rapid filling event. A comparison is presented for the data collected with $d_{orif^*} = 0.101$. The value assumed for the Manning coefficient was 0.011 sm$^{-1/3}$.

The comparison between the predicted and observed depth at $x^* = 0.953$ measured in the pre-bore motion experiments is shown in Fig. 7 (a). Good agreement was observed between the model and experimental results in each of the cases considered, particularly in the timing of the arrival of the pre-bore motion feature as well as the bore. The changes in the depth were generally well described, including the slight increase of the depth immediately prior to the bore arrival.

Figure 7 Comparison between the experimental and the numerical model results for $d_{orif^*} = 0.101$, $Q_i^* = 0.460$, $h_i^* = 0.76$.
(a) $h^*$ at $x^*$=0.953; (b) $V^*$ at $x^*$=0.649; (c) $\Delta H^*$ at $x^*$=0.953; (d) $h_{air}^*$ at $x^*$=0.953

Figure 7 (b) presents the predicted and measured flow velocities at $x^* = 0.649$. The model was
able to predict the experimental results with good accuracy. The initial slight increase in the velocity prior to the bore arrival resulted from the model prediction of the pre-bore motion associated with air pressurization, not from numerical diffusion. The peak velocity is slightly under-predicted, but the velocity variations caused by surge tank oscillations were well described.

A comparison between the predicted and measured air phase pressure (up to the instant of the bore arrival at the measurement location) for the pre-bore motion experiments is shown in Fig. 7 (c). As with the other variables good agreement between the model and the experiments is observed. The model under-estimated the pressure rise in cases when \( h_i^* = 0.809 \) (results not shown). Upon bore arrival at the surge tank, the measured pressure rises abruptly while the model assumes the air was totally evacuated from the system, and sets the air phase pressure to zero. There is also good agreement in the predicted pressure head variation at the invert of \( x^* = 0.953 \), as shown in Fig. 7 (d), even though the model is not able to represent the bore impact against the surge tank gate.

4.3 Predicting the interface breakdown feature

Interface breakdown experiments conducted by Vasconcelos (2005) ruled out effects at the system boundaries as contributing to the occurrence of IBD. The question arose as to what type of interaction would explain this phenomenon. It was realized that when the upstream propagating depression wave (such as shown in Figs. 5 and 6) on the free surface region encountered the pipe-filling bore, the inflow bore may no longer be strong enough to close the whole cross section of the pipe. As a result, the bore would continue as a free-surface bore, leaving a long air pocket on the top, the primary characteristic of the IBD feature.

The possibility of other flow features to alter the nature of the pressurization front was considered in the investigation by Cardle and Song (1988). They described the occurrence of a flow feature referred to as “interface reversal”, when the direction of the pressurization bore was reversed by the flow conditions at the bore vicinity. Unlike the IBD, its cause is not related to the air pressurization but to changes in the flow on the pressurized side of the bore. Consideration was given as to whether it is possible that the interaction between the pre-bore motion and the pipe-filling bore could result in the IBD. Consider the mass and momentum balance across the moving pipe-filling bore of speed \( V_s \). Continuity across the bore is given by

\[
A_1(V_1 - V_s) = A_2(V_2 - V_s) \tag{5}
\]

in which \( A_1 \) and \( V_1 \) are the area and flow velocity upstream of the bore, and \( A_2 \) and \( V_2 \) the area and flow velocity downstream of the bore. Solving for the bore speed \( V_s \) gives
The momentum conservation across the bore can be written as

\[ V_s = \frac{A_1 V_s - A_1 V_1}{A_2 - A_1} \quad (6) \]

\[ g \left[ A_2 \bar{y}_2 - A_1 \left( \frac{D}{2} + Z - h_{air} \right) \right] = A_1 (V_1 - V_s)(V_2 - V_1) \quad (7) \]

in which \( \bar{y}_2 \) is the depth of the centroid in the free surface region and \( Z \) the pressure head above the pipe crown on the water-filled side of the bore. Introducing Eq. (6) into Eq. (7) and after algebraic manipulation, the expression relating \( Z \) to the other variables is

\[ Z = \frac{A_2 \bar{y}_2}{A_1} - \frac{A_2}{A_2 - A_1} \frac{(V_2 - V_1)^2}{g} - \frac{D}{2} + h_{air} \quad (8) \]

In order for IBD to occur, the value of \( Z \) from Eq. (8) would need to drop below the value of \( h_{air} \), in which case air intrusion will occur along the top of the pipe. To determine whether this is possible, one would need velocities upstream and downstream from the pipe-filling bore at the moment of the IBD onset. Measurement of these velocities with two ADV probes upstream and downstream of the bore is exceedingly difficult to conduct considering the dimensions of the front. This prevents an experimental proof that the interactions between the bore and the depression wave result in the IBD feature.

However, the present experimental observations can be used to verify, albeit numerically, whether the interaction between the depression wave generated by the pre-bore motion and the pipe-filling bore can result in the IBD. This hypothesis was tested with the numerical model, which was able to predict the onset of the air intrusion caused by the interaction between the depression wave created by the air pressurization on the free surface of the flow and the pipe-filling bore interface. Vasconcelos (2005) presents a comparison between model predictions and observations for four separate experiments, one of which is presented in Fig. 8; in all four cases, the model predictions accurately reflect the test observations.

Figure 8 presents the first flow profile at \( t = 4.1 \) s \( (t^* = 0.275) \); the pipe-filling bore is already at 25% of the pipe length with the pre-bore motion noticeable at \( x = 10.5 \) m \( (x^* = 0.74) \). The two flow features meet at \( t = 8.2 \) s \( (t^* = 0.551) \), and the onset of the IBD is noticeable as the predicted pressure head drops below the pipe crown, implying the establishment of free surface flow behind the bore front. As time advances, the air pocket continues to expand, until the open-channel bore arrives at the surge tank and the resulting reflection entraps the air pocket at \( t = 12.9 \) s \( (t^* = 0.866) \). While the numerical model predicts the IBD occurrence at \( x = 8.7 \) m \( (x^* = 0.608) \), visual observations indicated the location of occurrence at \( x = 9.0 \) m \( (x^* = 0.628) \). This is considered a good agreement between the
model and the experimental results, considering the complexity of the problem.

Even though there are important limitations regarding air modeling in the proposed model, it is able to predict the pre-bore motion feature with velocity and pressure predictions close to the experimental measurements. It is also capable to predict the fundamental details of the interface breakdown process including the location of occurrence. The prediction indicates quite clearly that the transition from a pipe-filling to a free surface bore is created by the interaction with the upstream propagating depression wave and the bore front. The depression wave in turn is induced by the pressurization of the air above the initially partially full pipeline. Numerical models attempting to reproduce this behavior must include, at a minimum, the level of detail in the model presented above. It remains to be established whether more complex models are required to simulate the subsequent transport of the entrapped air pockets.

Figure 8 Prediction of bore advance with development of Interface Breakdown feature for $d_{orj^*} = 0.068$, $Q_{i^*} = 0.365$ and $h_{i^*} = 0.76$. (a) $t = 4.1$ s; (b) $t = 8.2$ s; (c) $t = 11.1$ s; (d) $t = 12.9$ s

5. Conclusions

The purpose of this investigation was to study in more detail the pre-bore motion and the interface breakdown phenomena that were first reported in Vasconcelos and Wright (2005). The characterization of the flow phenomena was performed with measurements of flow depths, velocity, and pressure in the water and air phases. The experimental results demonstrate that unless adequate venting conditions are provided in rapid filling tunnels, one may not neglect the effect of the air phase on the water motion.

Ventilation from the filling pipeline was controlled by installation of various nozzle sizes in a ventilation tower at one end of the filling pipeline. When smaller nozzle diameters were used to restrict
the air escape, both pre-bore motion and interface breakdown were observed, depending on the water inflow discharge. This illustrates the potential impact of ventilation on the system behavior, and indicates that the air phase dynamics may play an important role in the filling process in poorly ventilated systems. The initial water level has only a minor influence on the maximum pressures recorded at the surge riser, at least for the range of variables studied.

The experimental results indicate that interface breakdown results from an interaction between the depression wave associated with the pre-bore motion and the pipe-filling bore; this was confirmed by the predictions from the numerical model. When these two flow features interact, the strength of the pipe-filling bore is diminished. If IBD occurs, the original inflow front cannot continue to fill the pipe cross section and an open-channel bore develops. Thus, instead of an air intrusion, which implies the existence of a driving force that pushes the air into the top of the pipe-filling bore, the IBD feature can be perceived as a change in the nature of the inflow front which results in the collapse of a pipe-filling bore. The experimental results suggest that the pipe-filling bore front can be broken down by interactions between one or more waves within the sewers.

The numerical model successfully predicted the experimental measurements of depth, velocity and pressures in both the pre-bore motion and interface breakdown experiments. The model was also able to predict the onset of the interface breakdowns. The good prediction of the location of the intrusion onset illustrates the importance of the application of an appropriate numerical scheme in order to obtain precise timing and magnitudes of both the pipe-filling bore front and the air pressurization-induced depression wave. An important future improvement for a model to describe the rapid filling of storm systems will be the development of the ability to model air pocket formation and motion within stormwater tunnels. However, this appears to require the application of a different approach, possibly abandoning the one-dimensional formulation in favor of multi-dimensional models.

**Notation**

- $A = \text{Cross-sectional area}$
- $A_{fs} = \text{Cross-sectional area of free-surface flow portion}$
- $A_{orif} = \text{Air nozzle cross-sectional area}$
- $A_{pipe} = \text{Cross-sectional area of pipe}$
- $A_1 = \text{Cross-sectional area of flow upstream of pipe-filling bore front}$
- $A_2 = \text{Cross-sectional area of flow downstream of pipe-filling bore front}$
- $C_d = \text{Discharge coefficient of air nozzle}$
- $D = \text{Pipeline diameter}$
\( d_{\text{orif}} \) = Air nozzle diameter
\( d_{\text{orif}}^* \) = Non-dimensional air nozzle diameter
\( F \) = vector of conserved variables fluxes
\( g \) = gravitational acceleration
\( h \) = Water depth within pipe
\( h^* \) = Non-dimensional water depth within pipe
\( h_{\text{air}} \) = Air phase gage pressure head
\( h_c \) = Distance between free surface and centroid of flow cross-sectional area
\( h_i^* \) = Non-dimensional initial water depth within pipe
\( h_i \) = Initial water depth within pipe
\( H \) = Overall piezometric head, including air phase pressure head
\( H^* \) = Non-dimensional overall piezometric head, including air phase pressure head
\( L \) = Pipeline length
\( Q \) = Discharge
\( Q_i \) = Inflow discharge
\( Q_i^* \) = Non-dimensional water inflow discharge
\( Q_{\text{air}} \) = Air phase volumetric flow discharge
\( S \) = Vector of source terms
\( S_o \) = Channel bed slope
\( S_f \) = Energy slope
IBD = Interface breakdown
PBM = Pre-bore motion
\( t \) = Time from flow startup
\( t^* \) = Non-dimensional time from flow startup
TARP = Tunnel And Reservoir Project
\( U \) = vector of conserved variables = \([A, Q]^T\)
\( V \) = Water velocity measured by ADV probe
\( V^* \) = Non-dimensional water velocity measured by ADV probe
\( V_1 \) = Water flow velocity upstream pipe-filling bore front
\( V_2 \) = Water flow velocity downstream pipe-filling bore front
\( V_s \) = Pipe-filling bore front velocity
\( x \) = Distance from upstream reservoir
\( x^* \) = Non-dimensional distance from upstream reservoir
$Y = \text{Air phase expansion factor}$

$y_2 = \text{Depth of centroid in downstream portion of pipe-filling bore front}$

$Z = \text{Pressure head above pipe crown upstream pipe-filling bore front}$

$\rho_w = \text{Water density}$

$\rho_a = \text{Air density}$

**References**


