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Numeric Modeling of Water Mains Filling Considering Air Pressurization

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The filling of water mains represents a type of unsteady, two phase flow that normally follows maintenance procedures which require emptying the mains. This is performed carefully to avoid the formation of air pockets, which can cause high pressures in conduits and also reduce their conveyance capacity. Numerical modeling is an essential tool for the study of this kind of problem as a means of anticipating operational issues. Among the models proposed for this application are those of Liou and Hunt (1996), Izquierdo et al. (1999) and Vasconcelos (2007). Such models' applicability is limited due to the assumptions made in their development, which include simplified shapes of water filling fronts, and non-consideration of ventilation systems or air pressurization effects. This chapter will present a numerical model for the simulation of gradual water mains filling that allows for both a more realistic inflow front and the development of air pressurization. The model solves a system of ordinary differential equations which represent the advance of the inflow front, the development of air pressurization, and conservation of the air phase. The model uses Object Pascal and has a friendly and interactive user interface, and future tests will present a comparison between model predictions and laboratory measurements.

1.1 Introduction

Water mains are conduits designed to transport water or sewage between two operational units of a water supply system. They have a closed section and are intended to operate in a pressurized flow regime. Water flow may be due to gravity, if the topography of the land is favorable, or by pumping.

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Water mains are generally designed with the assumption that the flow is steady, single phase and uniform. Flow may become unsteady due to changes in the operational conditions of the system, such as the abrupt closing of a valve. Often water contains some amount of dissolved air, but some amount of free air may also exist as small air pockets or bubbles. Even in transient flow conditions, this volume of air is usually not enough to cause operational problems as the flow velocity is able to remove this air.

Larger air pockets may form during the water main filling process, which follows maintenance procedures that require emptying the mains, and also happens in the commissioning of the system. Finally, partial filling of water mains may occur in systems that operate with intermittent water supply but constant demand, with the pipes effectively operating as reservoirs.

When filling water mains, it is essential to be cautious because there is the possibility that entrapped air pockets may cause operational problems. The high compressibility of air may lead to damagingly high pressures if air pockets are compressed by surrounding flow. Air pockets may also accumulate in unventilated pipes, creating barriers to the flow, increasing the head loss and reducing the conveyance of the system.

In order to avoid such operational issues, engineers include air valves along the water main, particularly at high points and slope changes, to let the accumulated air escape (Tullis, 1989). However, the design and distribution of these valves are mainly based on generic guidelines, and rely to some extent on the designer's experience. In addition to high points and slope changes, it is anticipated that other points could also accumulate air during filling events. The lack of a more complete understanding of the interactions between air and water phases, and the location of entrapped air pockets, may lead to the operational issues described above.

1.2 Objectives

This chapter presents the results of ongoing research on numerical models to simulate the filling of water mains. The present model aims to include interactions between the air phase and the water phase during the filling process, applying a simple unsteady framework to handle two phase flows based on a lumped inertia approach for unsteady water flow simulation and the ideal gas law to simulate the air phase. The model requirements are:

1. Use more realistic assumptions then the correspondent ones used in the current lumped inertia pipeline filling models;
2. Consider the effects of air pressurization; and
3. Create a user friendly model able to quickly simulate pipeline filling problem.

1.3 Literature Review

Models of conduit filling include those of Liou and Hunt (1996), Izquierdo et al. (1999) and Vasconcelos (2007). Other models were developed in the context of stormwater runoff and drainage conduits, one example being the work by Zhou et al. (2002).

One of the first models for the simulation of water main filling was proposed by Liou and Hunt (1996). It applied to the filling of long water mains with variations in topographic profiles. According to the authors, the model was applicable when the flow velocity is high enough to prevent the intrusion of air in the inflow front. The model assumes perfect air ventilation (remaining at atmospheric pressure) and that the inflow front remains well defined and vertical, resembling a water piston.

The limitation of that model is mainly the piston-like inflow front. This assumption may not well represent the actual shape of the inflow front. Guizani et al. (2005) conducted several experiments on the filling of water pipelines with different inflow conditions and slopes. In all cases the filling front shape resembled a wedge, similar to a dam-break front propagating within the pipe. Guizani et al. (2005) point out that a vertical interface would be a valid assumption only if the flow rate within the pipe is very large.

In the pipeline filling model by Izquierdo et al. (1999) the goal was to simulate the filling of pipelines considering the hypothesis that water accumulation in the lower points of the water main leads to the creation of air pockets. The pockets were located between the points of water accumulation and they were highly compressed by the surrounding water columns as the flow was initiated. Izquierdo et al. (1999) concluded that the smaller is the initially trapped air pockets, the greater are the pressure peaks in the system, as pointed out in an earlier work by Martin (1976). The model assumes that the transition interface between phases remains well defined and that the entrapped air does not intrude on the water advance.

This model improved on that of Liou and Hunt (1996) but it has limitations. In practice, water accumulation in lower points should be avoided prior to pipeline filling events since this condition may result in strong air pressurization. Moreover, if water accumulation is anticipated, it is unlikely that a water works maintenance team would perform the filling operation in an abrupt fashion, which would invalidate the simplification of an inflow interface with no air intrusion. Moreover, the Izquierdo et al. (1999) model neglects ventilation in the water main, which is a limitation since air valves are commonly found in water mains.

Vasconcelos (2007) proposed a model that has the capacity to simulate unsteady flow in both regimes (pipes pressurized or at atmospheric pressure). The model was implemented using the finite volume method to solve an adaptation of the Saint-Venant equations, which were initially proposed to model the transient flow of rivers and channels. Conceptual models such as Two-component Pressure Approach (Vasconcelos et al., 2006) expand the applicability of these equations to the conditions of pressurized conduits. The proposed model did not make any assumptions regarding the shape of the air-water front, and can thus predict the initial positions of entrapped air pockets. The limitation of the Vasconcelos (2007) model is that it does not consider the effects of air pressurization, assuming an ideal ventilation system. This assumption does not match the reality of many situations where the ventilation is designed empirically and works with limitations.

The rapid filling of stormwater sewers is an application that has significant similarities with water pipeline filling problems, and has also been investigated. Li and McCorquodale (1999) developed a model to simulate the pressure transients due to the transition from free-surface to pressurized flow inside the sewer conduit. The authors proposed a mathematical model based in the assumption of rigid water columns for the liquid phase and compressible air pockets for the gaseous phase. The study analyzes continuously surges due to the entrapped air pocket and considers the movement of the air pockets. The model extended and refined the previous rigid column approach proposed by Hamam and McCorquodale (1982) that adopted the hypothesis of a stationary bubble. Li and McCorquodale (1999) also present a physical model that confirmed the possibility of high pressures transients due to the presence of air cavities in the sewer conduit. The model of Li and McCorquodale (1999) considers only the ventilation provided at manholes.

Zhou et al. (2002) conducted experimental and numerical studies on the rapid filling of a short and horizontal conduit with limited air ventilation. The filling model used was also based on the lumped inertia approach, with the additional consideration of air pressurization effects. The model has the same limitation in the inflow interface, assuming a vertical inflow front in the filling process, but was effective in predicting the peak pressures during the filling events, even though was unable to predict the location of entrapped air pockets. Further work by Zhou et al (2004) introduced a vertical pipe in the apparatus in order to investigate the effect of the vertical conduit in the air-water flow condition, but the behavior of the system and the results did not change considerably.

In other context, multiphase models have been developed to simulate the slug flow in oil or gas transport through pipelines, one example being the work by Issa and Kempf (2003). However it is uncertain to what extent such models are able to replicate relevant flow features during pipeline filling problems, such as flow regime transition fronts and hydraulic bores.

1.4 Methodology

The proposed model aims to simulate the filling of a pipeline, with a simple geometric configuration, with a single low point. The initial condition corresponds to a totally empty water main and the boundary conditions are: partial opening of a valve at the upstream end of the pipeline; and brink depth discharge conditions at the downstream end. The proposed solution methodology divides the filling process into four phases, as presented below.

1.4.1 Phase 1: Free Surface Flow

The filling initiates with an unsteady flow coming from the reservoir to the first low point of the main. In this initial period, the water flows under atmospheric pressure, as seen in Figure 1.1.

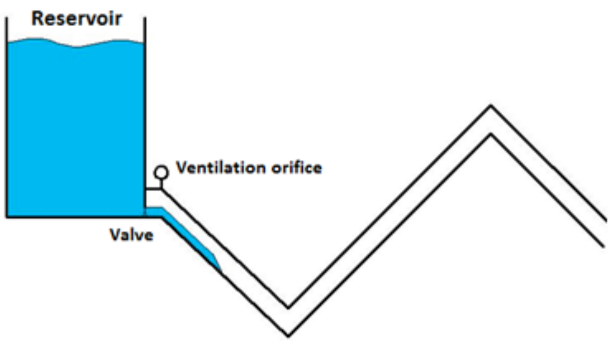

Figure 1.1 Free surface flow (Phase 1).

This free surface flow is simulated using the kinematic wave equation:

$$\frac{\partial Q}{\partial t} + K_c Q^{0,4} \frac{\partial Q}{\partial x} = 0 \tag{1.1}$$

where K_c is defined by:

$$\frac{1}{K_c} = \frac{3}{5}\left(\frac{nP^{2/3}}{\sqrt{S_f}}\right)^{3/5} \tag{1.2}$$

where:

Q = discharge,
n = Manning's coefficient,

S_f = slope of the energy line, and
P = wetted perimeter.

The choice of the kinematic wave was motivated by the fact that this simple alternative is accurate for free surface flow in sloped water mains, in which predominant forces are most likely weight and frictional forces.

1.4.2 Phase 2: Water Accumulation

The second phase starts when the flow reaches the first lower point of the water main. The water then accumulates and creates a small pool, which has a surface similar to the union of two half ellipses, as illustrated in Figure 1.2.

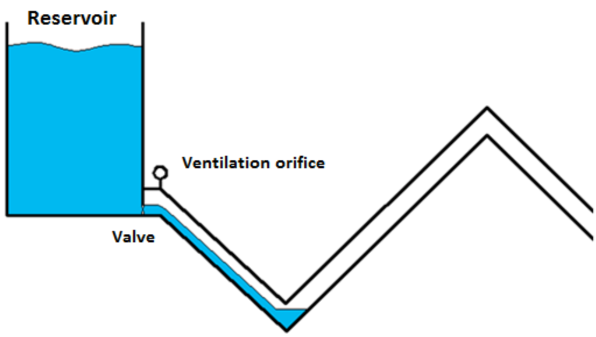

Figure 1.2 Sketch of water accumulation in the lower point (phase 2).

The water pool accumulation volume necessary to block the ventilation of the air mass upstream is calculated with a geometrical approximation. It is assumed that ventilation is blocked when the pool volume is equal to the sum of the two halves of cylinders which correspond to diagonal slices of the pipe reaches upstream and downstream from the low point. The volume of water that reaches the pool is calculated at each time step to verify when the accumulated volume matches the sum of those two half-cylinders.

1.4.3 Phase 3: Pocket Compression

This is the most important phase in the analysis of the proposed model. When the water accumulation blocks the upstream ventilation of the air mass, it is assumed that the lower water accumulation can be simulated with a lumped inertia approach. The air pocket is compressed by the water column and it tends to escape through the ventilation orifice upstream. The air pocket will pressurize more or less depending on the efficiency rate of the ventilation system. The air pressurization and the air discharge will be calculated by this model similarly to the approach used by Zhou et al. (2002), based on the ideal gas law.

The water accumulates at the lower point unevenly in the two legs of the water column due to the air pocket pressurization. The distribution is described in this model using conservation of mass and momentum. The flow that is admitted upstream is reduced due to the air pocket pressurization. As this flow rate is reduced, the air volume displacement decreases and air pressurization is diminished. Then the flow rate increases again, triggering an increase of air pressure and repeating the pressure oscillation cycle. The model assumes that the pool interface remains horizontal but the water level in each side of the low point increases with time.

The lumped inertia approach is a method which simplifies the partial differential equations that describe the transient flow in closed conduits to only one ordinary differential equation (Wylie and Streeter, 1993). This approach uses conservation of momentum as a basis, with the conditions of incompressibility of water and complete rigidity of the walls of the conduit. Under these conditions, Equation 1.3 can be written.

$$\frac{dQ_{col}}{dt} = \frac{gA}{L}\left(H_m - H_j - H_a - f\frac{L}{D}\frac{Q_{col}\left|Q_{col}\right|}{2gA^2} \right) \qquad (1.3)$$

where:

H_m = piezometric head at upstream,
H_j = piezometric head at downstream,
H_a = air phase pressure head (gauge),
Q_{col} = rigid column discharge,
L = length of the pipe,
D = diameter of the conduit,
g = acceleration due to gravity, and
f = Darcy-Weisbach friction factor.

The modification of the air pocket volume is calculated from the advance of the rigid column of water, considering that this volume varies due to the compression imposed by the liquid. This is expressed by Equation 1.4.

$$\frac{dV_a}{dt} = -Q_{in} + Q_{col} \qquad (1.4)$$

where:

V_a = air pocket volume, and
Q_{in} = flow rate admitted from the reservoir.

Assuming that ventilation is not very efficient, the pocket of air formed in the end of the pipe would suffer pressurization. The analytical model proposed for the air phase is based in the work of Martin (1976) and Zhou et al. (2002). Equation 1.5 shows the change in the pressure of the air pocket.

$$\frac{dH^*}{dt} = -k\frac{H^*}{V_a}\cdot\frac{dV_a}{dt} - k\frac{H^*}{V_a}Q_a \qquad (1.5)$$

where:

H^* = absolute pressure of air,
Q_a = discharge of air through the orifice, and
k = polytrophic coefficient.

The model also assumes that the air phase obeys the ideal gas law, thus $pV_a{}^k = const$, where p is the absolute gas pressure, V_a is the air volume and k is the polytrophic coefficient, assumed here to be 1.2.

The air discharge depends on the relation $H^*/H_b{}^*$, where $H_b{}^*$ is the absolute initial air pressure. If $H^*/H_b{}^* < 1.89$ the discharge could be expressed by Equation 1.6.

$$Q_a = C_d A_o Y\sqrt{2g\cdot\frac{\rho_w}{\rho_a}\cdot\left(H^* - H_b^*\right)} \qquad (1.6)$$

where

Cd = discharge coefficient of the orifice,
Ao = area of the orifice,
ρ_w = density of water, and
ρ_a = density of air.

The choking factor Y is calculated by Equation 1.7.

$$Y = \sqrt{\frac{k}{k-1}\cdot\left(\frac{H_b^*}{H^*}\right)^{2/k}\cdot\frac{1-\left(H_b^*/H^*\right)^{(k-1)/k}}{1-\left(H_b^*/H^*\right)}} \qquad (1.7)$$

When the air pocket pressurization grows to the point where $H^*/H_b{}^* > 1.89$, the orifice is classified as choked. The choked flow indicates a limiting condition, which occurs when the flow rate of the fluid does not increase with a decrease of downstream pressure, considering that the upstream pressure does not suffer variation. If $H^*/H_b{}^* > 1.89$ the discharge of air can be defined by Equation 1.8.

$$Q_a = C_d A_o\sqrt{2g\frac{\rho_w}{\rho_a}H^*}\cdot\sqrt{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} \qquad (1.8)$$

Figure 1.3 presents a sketch of phase 3 with all the differential equations and the progressive filling front, which advances toward the next high point, together with the regressive filling front, which advances upstream and compresses the next entrapped air pocket.

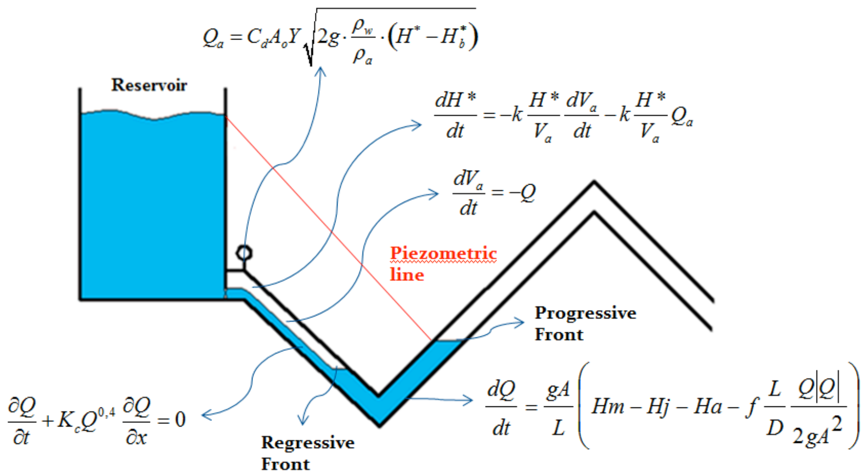

Figure 1.3 Schema of the process with all the equations (phase 3).

1.4.4 Phase 4: Pressurized Flow

When the progressive front head reaches the highest point of the main, a brink depth condition is established in the flow. The simulation continues until the system reaches a steady state condition where the admitted inflow is equal to the value of the discharge at the downstream end. Figure 1.4 shows the last step of filling as predicted by the model. The sharp crested weir discharge was calculated by equation (1.9).

$$Q = k * h^{3/2} \tag{1.9}$$

where k is a factor that varies with the width of the crest assuming the maximum value of 1.59 for this particular geometry and

$$k = \frac{2}{3} C_d * L * \sqrt{2g} \tag{1.10}$$

where:

C_d = discharge coefficient,
L = width of the discharge crest, and
h = piezometric head.

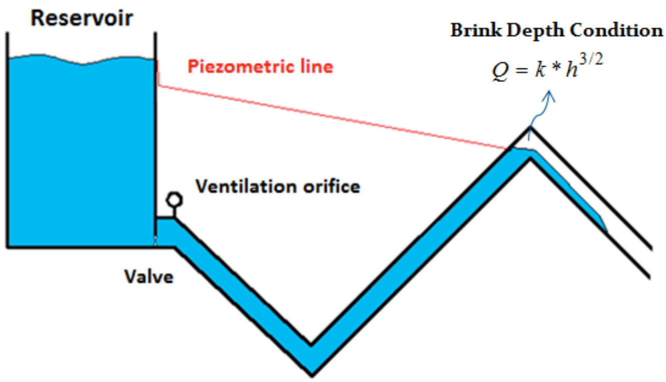

Figure 1.4 Final step of the filling model (Phase 4).

1.5 Results and Analysis

The model proposed in the methodology of this article was implemented in Object Pascal. In order to verify the operation of the model against a real problem, the model was applied to a system based on the experimental apparatus of the research of Lima (2009). Figure 1.5 and Table 1.1 show the parameters and characteristics of the system.

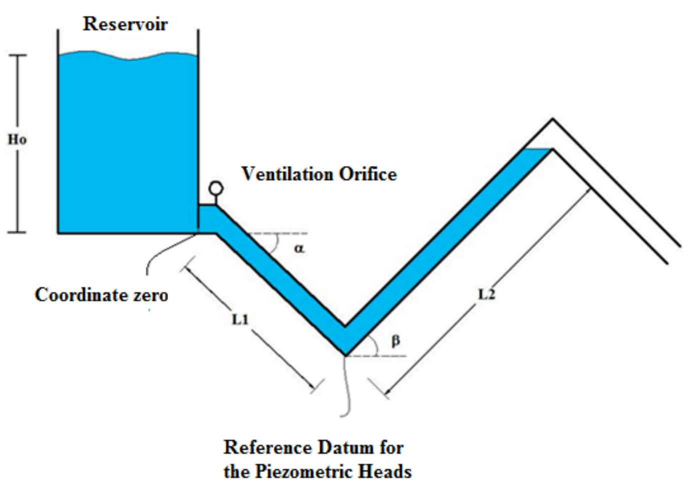

Figure 1.5 Sketch of the reference for model parameters.

Table 1.1 Model parameters and values.

Apparatus geometry parameter	Value
Reservoir head - Ho (m)	1.2
Length L1 (m)	9
Length L2 (m)	5
Diameter (m)	0.09
Manning`s coefficient	0.012
Slope alpha	2.5
Slope beta	11
Polytrophic coefficient	1.2
Friction factor	0.012
Gravity (m^2/s)	9.81

Six different settings were considered by varying the inflow and orifice ventilation diameters, as presented in Table 1.2

Table 1.2 The simulated parameters.

Parameter	Range Tested
Inflow (*Qi*)	1.5 L/s and 2.3 L/s
Ventilation Orifice Diameter (*Do*)	0 mm; 8 mm; 24 mm

The simulation variables included: the evolution of the admitted inflow; air volumetric discharge rate; movement of the filling column; and the pressures in the main. The results for the two different admitted inflows (*Qi* = 2.3 and *Qi* = 1.5) showed similar behaviors. Due to space limitations, this chapter will only present the results for the 2.3 L/s inflow.

The model starts with an empty pipe so the 8 initial seconds are the time necessary for the admitted inflow to fill the small pool and pressurize the water main. The simulation runs until the admitted inflow matches the weir flow, indicating that the main is fully pressurized or the system is at a steady state

1.5.1 Air Volume Results

Figures 1.6, 1.7 and 1.8 represent the changes in the volume of the air pocket for *Do* = 0 mm (zero ventilation), *Do* = 8 mm and *Do* = 24 mm, respectively, and admitted inflow equal to 2.3 L/s.

Figure 1.6 shows that the air pocket volume oscillates as the pressure applied by the water column oscillates, resembling a mass-spring system. The volume of air in the pocket does not vary significantly as there is no ventilation and the compression head is small. For the other two cases, air volume decays in a quasi-linear fashion. As expected, the system with the larger orifice size expels the air pocket more rapidly. The lumped inertia model for the water column showed instability when the air volume approached zero.

When this condition happened, the model automatically assigned zero air volume.

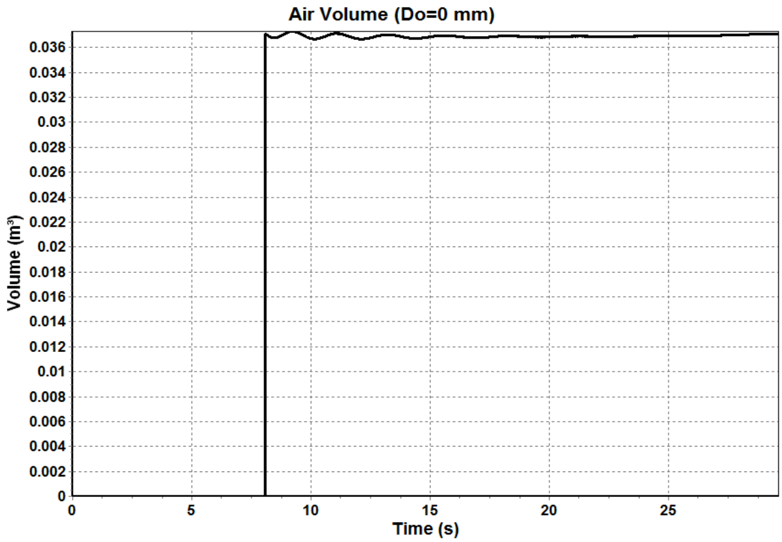

Figure 1.6 Evolution of air volume (*Do* = 0).

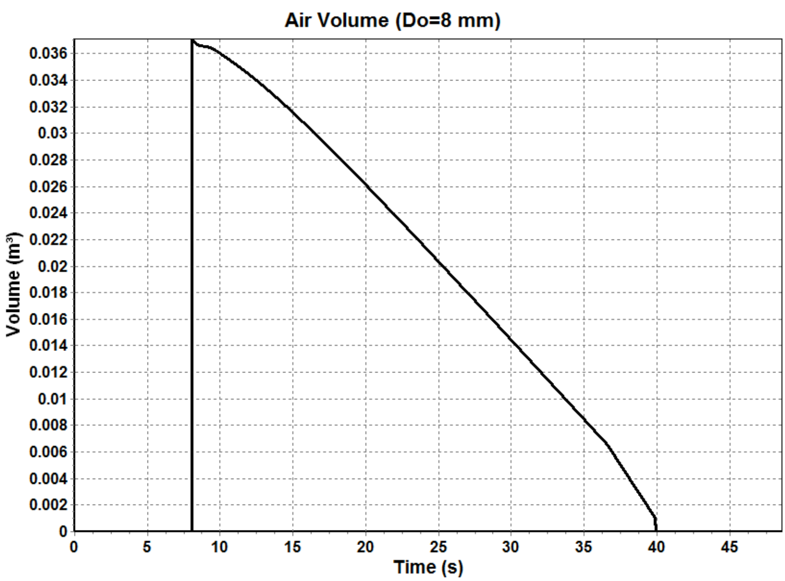

Figure 1.7 Evolution of air volume (*Do* = 8).

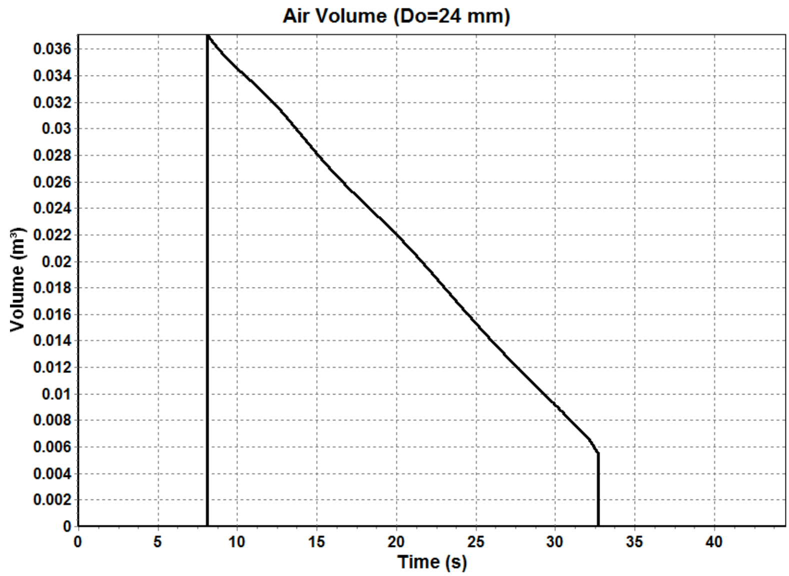

Figure 1.8 Evolution of air volume (*Do* = 24).

1.5.2 Flow Rate Results

The model evaluated three relevant discharges for the analysis of the water main filling process: the admitted inflow, the rigid column discharge and the air discharge. Figure 1.9 shows the schema, with the notation which is used, and Figures 1.10, 1.11 and 1.12 illustrate system inflows and discharges for the three orifice sizes.

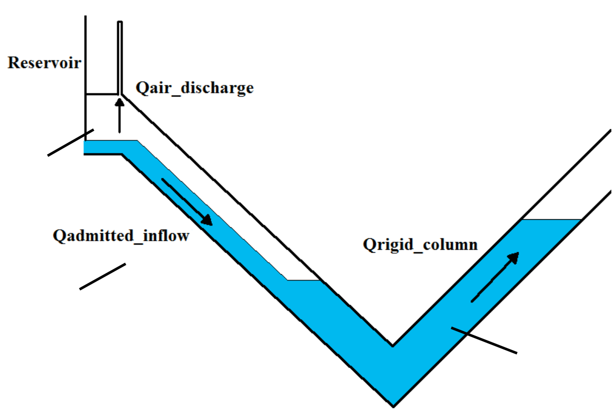

Figure 1.9 Scheme with notation.

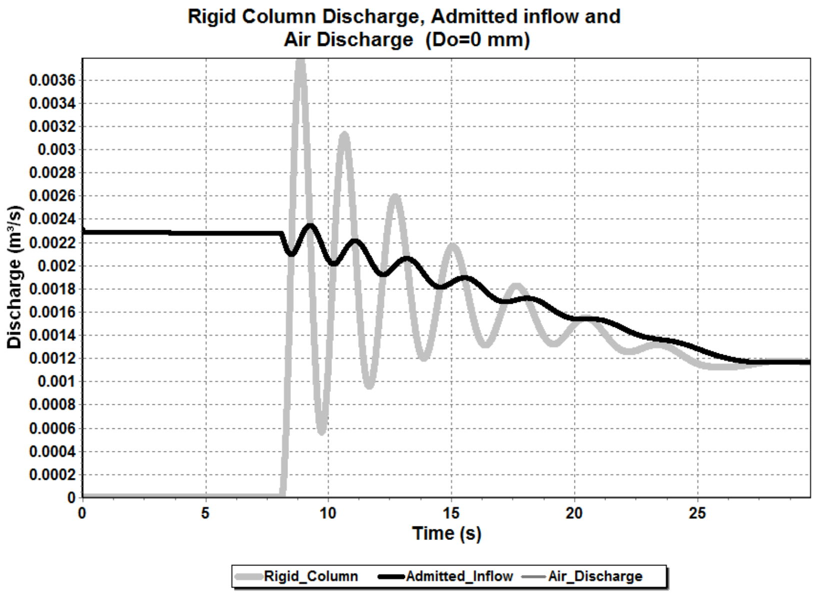

Figure 1.10 Evolution of the discharges (*Do* = 0).

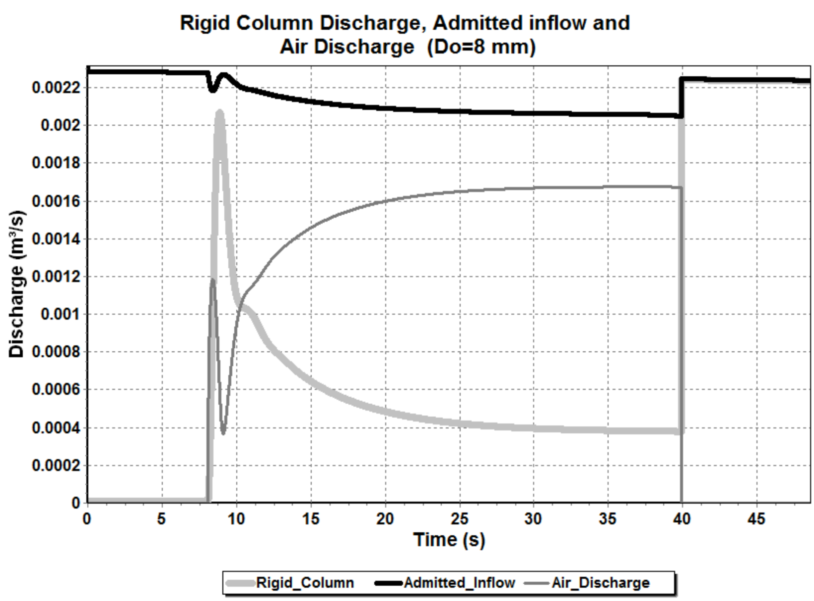

Figure 1.11 Evolution of the discharges (*Do* = 8).

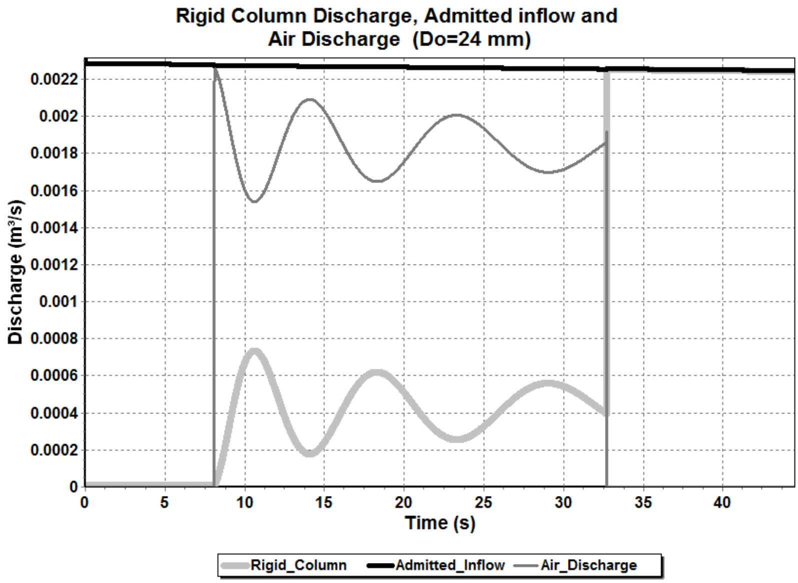

Figure 1.12 Evolution of the discharges (*Do* = 24).

Figure 1.10 shows that the air discharge is equal to zero due to the absence of ventilation, and that the column discharge oscillates too much at the beginning due to the fluctuations on the air pocket pressure and to the small column inertia. The model predicts a decrease in the admitted inflow of 50% during the period of the filling due to air pocket pressurization. For the case presented in Figure 1.11, where the air pocket is ventilated, it can be verified that the column discharge decreases and the air discharge increases. This is consistent with the increase in air pressurization, which in turn is linked to the small orifice size.

Figure 1.12 shows a situation in which oscillations still exist, but the effects of the air pressure are less pronounced. Oscillations that appear are entirely due to inertial causes, much like a U-tube system. Another observation in Figures 1.11 and 1.12 is that the magnitude of the admitted inflow equals the sum of the column discharge and the air discharge. This event occurs because of the small compression of the air, but in real time systems, with higher pressures, this situation might not be observed

1.5.3 Pressure Head Results

The progressive front head, regressive front head and the air pressure head were calculated relative to the datum at the low point. Figure 1.13 shows the schema and variables simulated and Figures 1.14, 1.15 and 1.16 present the evolution of those heads for the different sizes of the orifices (*Do* = 0 mm, *Do* = 8 mm and *Do* = 24 mm) during the water main filling process.

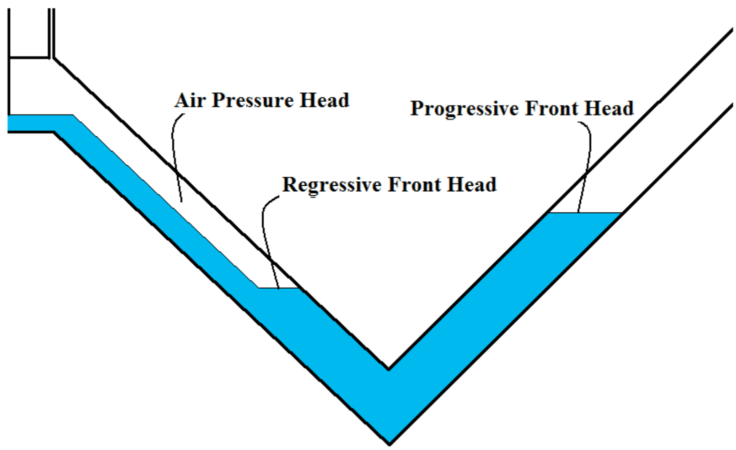

Figure 1.13 Schema with notation.

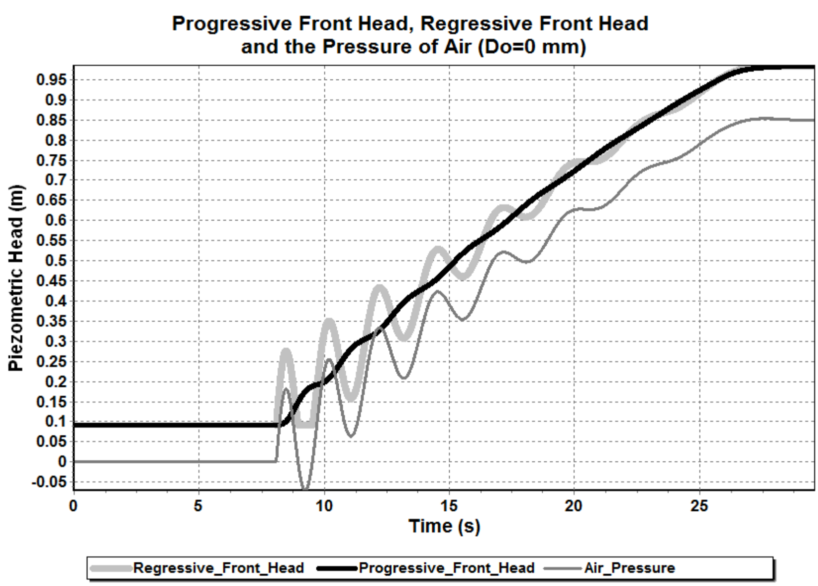

Figure 1.14 Evolution of the piezometric heads (*Do* = 0).

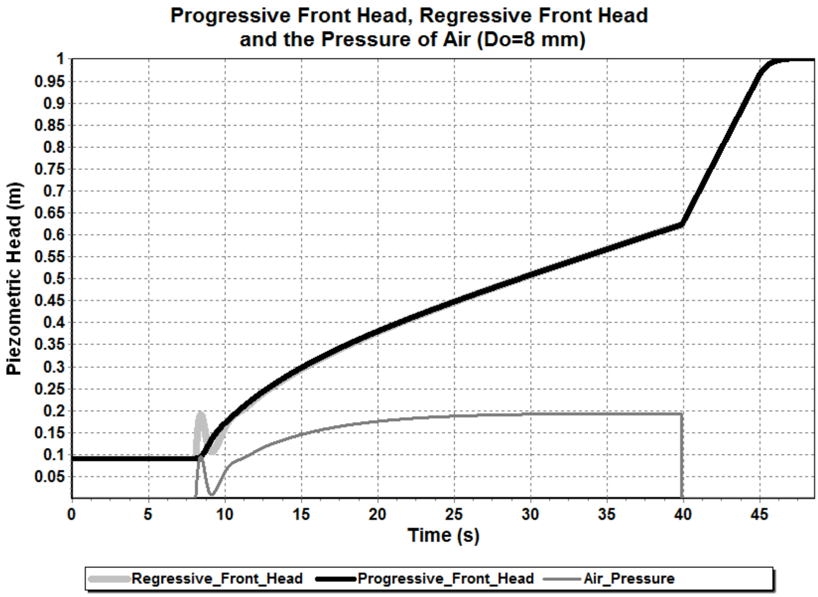

Figure 1.15 Evolution of the piezometric heads (*Do* = 8).

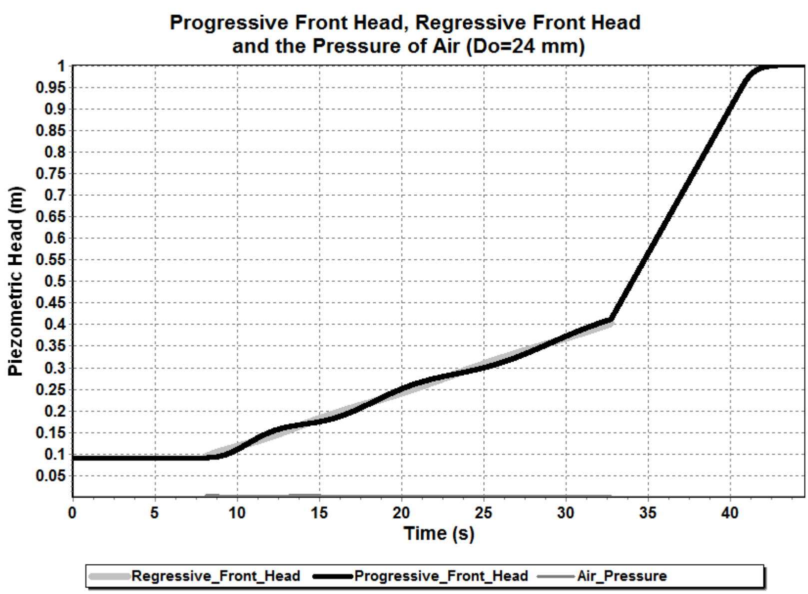

Figure 1.16 Evolution of the piezometric heads (*Do* = 24).

Figures 1.14 and 1.15 indicate that the air pressure interferes directly with the regressive front head. Such variables interact and complement themselves reflecting the behavior of a two phase system. It is also important to notice that even with a low admitted inflow the air pressure increases substantially considering the scale of the system (8.35 kPa, or 0.85 m water, for the case without ventilation). This should become even more relevant if the model is to be applied in a larger conduit.

Unlike the other plots, Figure 1.16 shows that the 24 mm orifice is sufficient to prevent the pressurization of the air pocket. The small differences that exist between the progressive and the regressive front heads are due to inertial oscillations.

1.5.4 Predictions of the Filling From Location

The coordinates of the progressive and regressive front were plotted in relation to the position of the valve at the upstream entrance. Figures 1.17, 1.18 and 1.19 present the front location for the different ventilation conditions.

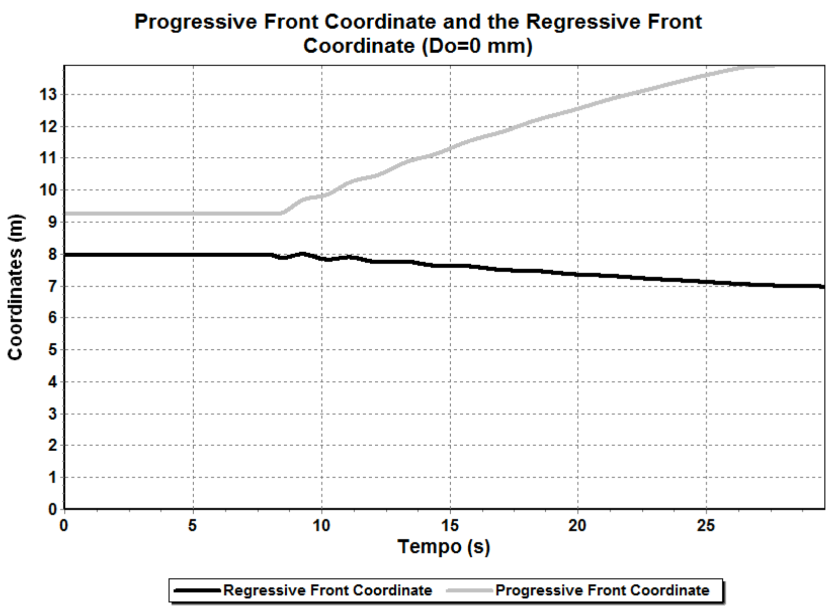

Figure 1.17 Evolution of the front coordinates (*Do* = 0).

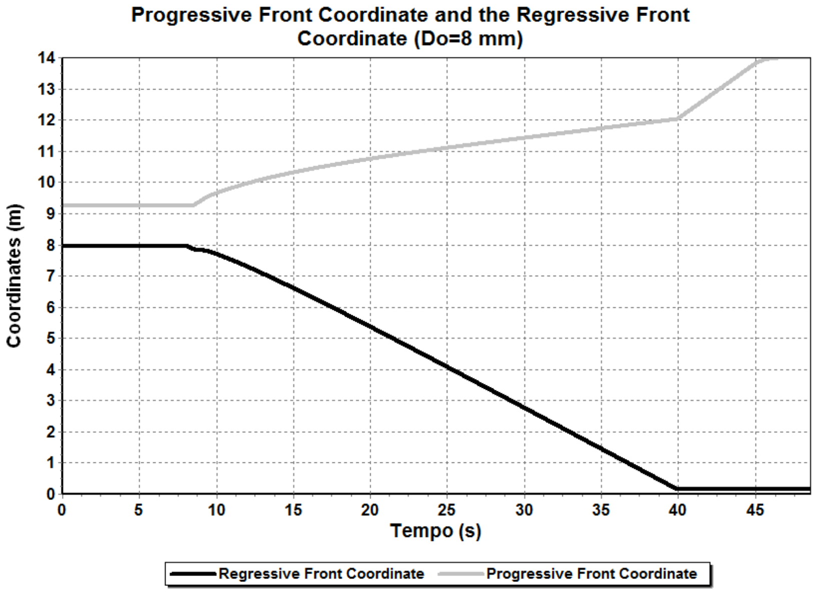

Figure 1.18 Evolution of the front coordinates (*Do* = 8).

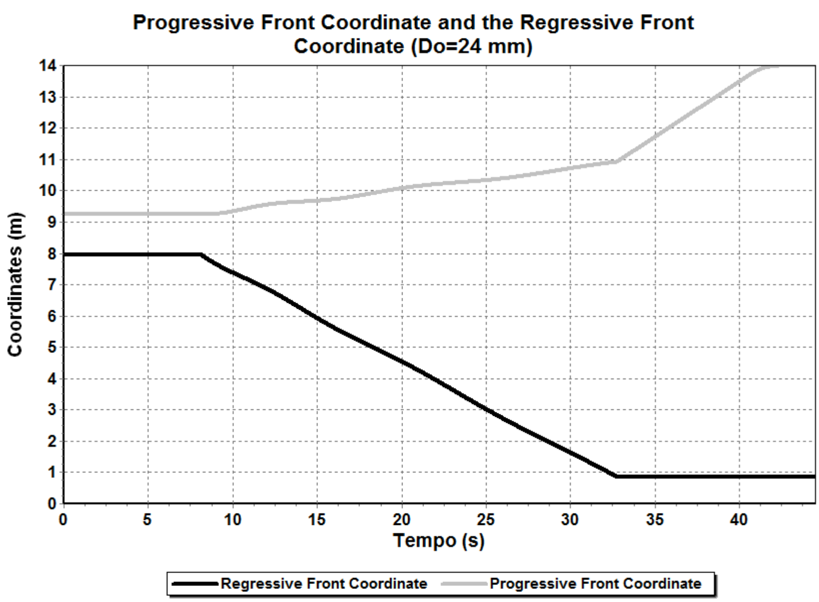

Figure 1.19 Evolution of the front coordinates (*Do* = 24).

In the three figures above, there is horizontal range that represents the initial coordinates of the column; at these initial time steps, the progressive and regressive fronts are not yet formed. In Figure 1.18, it can be verified that the regressive front coordinate only moves 1 m (about 11 diameters) in the direction of the reservoir due to the air pressurization.

For the other two orifice sizes, the regressive front moves faster towards upstream because of the smaller slope at the upstream reach of the pipeline. When the air pocket escapes completely the progressive front moves more rapidly in the direction of the pipeline end, as anticipated.

1.6 Conclusions and Future Work

Filling of water mains is a type of transient unsteady flow and the knowledge of its behavior is important since it occurs frequently and can be the cause of operational problems. Experimental and numerical researches are still required to increase the knowledge of the interactions between air and water during the filling. This study aims to contribute towards the understanding of the transient flows in pipelines with ventilation restrictions while they are being filled.

The simulation results indicate that, in situations of insufficient ventilation, the air pressure during filling grows considerably, causing admitted inflow reduction, in comparison with cases where ventilation is greater. This research also found that the orifices tested (8 mm and 24 mm) have very different characteristics. For the former orifice, the ventilation was inefficient, resulting in a highly pressurized air pocket. For the latter, the ventilation orifice was too large and there was not any significant air pressurization. This model could be used for a systematic study that would enable the determination of the minimum ventilation requirement that can allow air elimination without over-pressurization.

The model results seem to be consistent, and require, as it was intended, little computational effort, having also a simple user interface. This factor is important in order to facilitate the adoption of such a model by water works, which would then have more confidence in performing water main filling operations. Future versions of this program may help to predict how long the pocket remains in the main and the corresponding evolution of volume and pressure during the filling events.

This study represents only an initial step in the path of improving our understanding of two phase flow in closed pipes. One future objective is to compare these numerical results with experimental data, so this proposed model can be calibrated and verified. It is recommended that future work on this research advances towards the creation of a more general model that simulates the filling of a water main with several high and low points.

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