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Experimental Investigation on Surcharging of Flowing Sewers

Jose G. Vasconcelos and Steven J. Wright

The rapid filling of large diameter stormwater conduits has been associated with a number of operational problems including structural damages and the return of stormwater to grade through vertical inflow or ventilation shafts. There have been limited investigations to date related to the flow mechanisms that lead to these problems. Laboratory investigations have been previously conducted to examine various aspects of this rapid filling problem but generally are conducted to examine a particular aspect of the overall problem. It is generally not feasible to reproduce a complete system at a reasonable scale so any laboratory study necessarily is an idealization of a real system. An outstanding question is to what extent the experiments performed to date are representative of the actual flow conditions in stormwater systems undergoing rapid filling. This investigation presents a series of exploratory experiments conducted for conditions that were designed to more closely approximate the expected flow in real stormwater systems. In particular, the objective was to examine behavior with inflow from multiple sources. These conditions were generated by creating a surcharging front at an intermediate point in a system with an initial steady state, gradually varied flow. Measurements of pressure and velocity as well as visual observations confirmed the possibility of air entrapment and pressurization, which in turn can pose limitations to the ability of typical numerical models to describe such flows. Experimental results are presented along with a description of observed flow phenomena.

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10.1 Introduction

The problem of extreme inflow conditions in stormwater systems has been the subject of various experimental investigations to date. It has generally been assumed that most severe flow conditions are initiated by an abrupt transition between free surface and pressurized flow states through a hydraulic bore and the experimental designs have therefore concentrated on simple procedures that can be used to develop this type of flow regime transition. Most actual stormwater systems will be subjected to an inflow hydrograph consisting of an increase in flow from a small rate up to a peak value followed by a gradual decline in discharge.

Some of these previous experiments were based on the sudden introduction of inflows into systems with initial still water conditions. This approach essentially approximates the inflow hydrograph as a low initial flow that produces an initial volume of water in the system with relatively low flow velocities followed by a rapid increase in flow up to the peak discharge. These investigations include the works by Wiggert (1972), Arai and Yamamoto (2003) and Vasconcelos and Wright (2003). Such conditions are not expected in practical stormwater applications since drainage sewers are normally initially in flowing conditions prior to a rapid increase in the flow. These flowing conditions produce an initial water surface profile that is non-horizontal and this could potentially have a major impact on the subsequent evolution of the flow following the increase in discharge.

In a similar experiment, Zhou et al. (2002, 2004) have represented the flow regime transition in sewers by introducing inflow with a large upstream pressure head into an initially empty pipe. This is an even more unlikely condition in stormwater systems, since the lower flows near the beginning of the inflow hydrograph should produce some initial volume within the system prior to a flow regime transition occurrence.

Other experimental investigations, such as Cardle et al. (1989), Li and McCorquodale (1999), and Trajkovic et al. (1999) have generated the flow regime transition by suddenly blocking the end of a flowing pipeline. Even though such conditions could represent the accidental shutdown of a stormwater pumping facility, most of the flow regime transition events in stormwater systems are likely to be associated with an increase in the inflow.

A fundamental problem in laboratory modeling of transient events in stormwater collection systems is that the complete reproduction of an entire system with typical horizontal dimensions of several kilometers or even tens of kilometers would require model pipe diameters too small to avoid

significant scale effects. Therefore, any laboratory investigation inevitably relies on some idealization of reality. A key question relates to whether these idealizations result in laboratory results that are no longer representative of important system behavior. Since there are only extremely limited field measurements on transient events in actual systems, it is not clearly understood what the key aspects of system behavior might be that should be considered in system design. Experimental design should be carefully considered to represent flow conditions as closely as possible, particularly if the objective is to use the experimental observations to identify flow. One of the aspects that is representative of actual systems is that inflow is allowed through a number of discrete points. A flow regime transition could be initiated at any one of these or it is also possible that it could occur at more than one location at close to the same time, allowing for complex flow interactions. The experimental study reported in this chapter, while necessarily involving an idealization of system details, attempted to examine the occurrence of flow regime transition generated by an intermediate inflow along a pipeline that exhibited initially flowing conditions.

Flow regime transition conditions in a combined sewer system have been observed on several occasions in the Jefferson Avenue Interceptor in the Detroit Water and Sewer Department system in the state of Michigan. Figure 10.1 indicates a schematic of the system just north of the Macomb County/Wayne County border located north of the city of Detroit. The events were noted by observations of sewer manhole covers being blown off the Jefferson Avenue Interceptor or the Jefferson Avenue Relief Sewer in the vicinity of the Chapaton Pumping Station. Flow is from north to south towards the Detroit Wastewater Treatment Plant. These occurrences were not observed prior to the completion of the Jefferson Avenue Relief Interceptor. The source of these occurrences was identified as unregulated inflows into the Jefferson Avenue Interceptor several kilometers to the south of the area indicated in Figure 10.1. These inflows are sufficient to create a flow regime transition with a hydraulic bore propagating upstream as indicated in Figure 10.2. The flow depths are recorded at 10 minute intervals at three metering locations, two of which are indicated in Figure 10.1 and FM 03 is further upstream. The coarse temporal resolution does not capture the details of the hydraulic bore but the data including the timing from one location to another are consistent with the propagation of a pipe-filling bore that travels from downstream to upstream. The lack of observation of these events prior to the construction of the Jefferson Avenue Relief Sewer is attributed to the reduced capacity in the original system not

allowing the Jefferson Avenue Interceptor to flow in a free surface state when the downstream event was initiated.

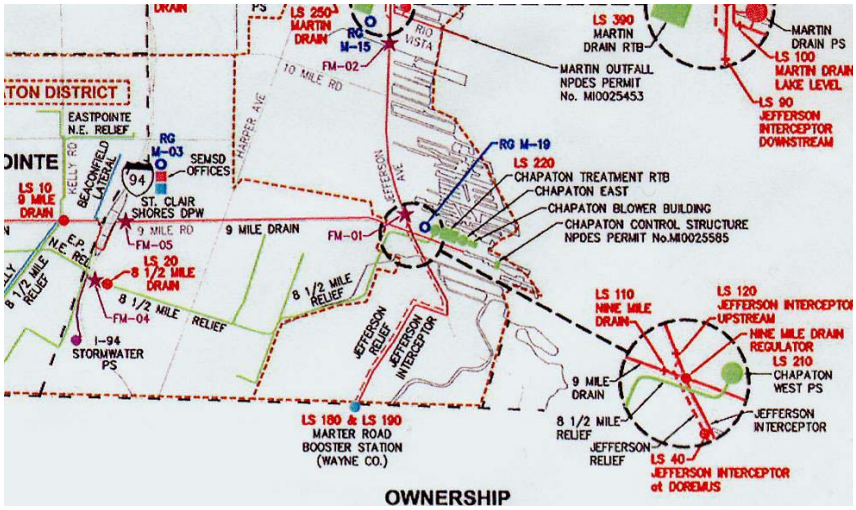

Figure 10.1 Schematic of Jefferson Avenue Interceptor in southern Macomb County, Michigan.

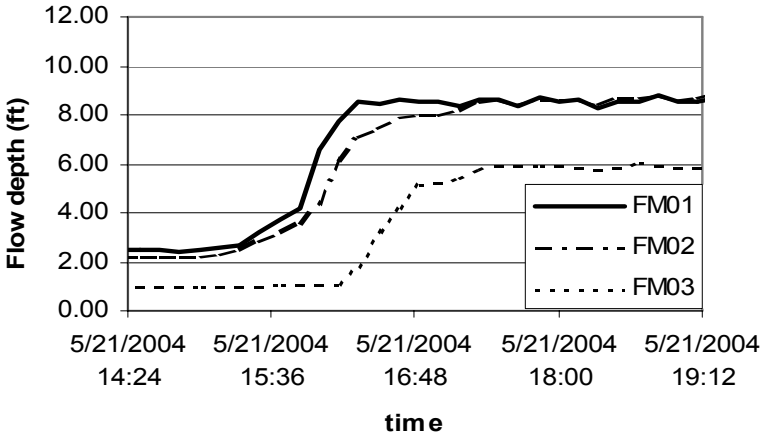

Figure 10.2 Flow depth versus time at three meter stations along the Jefferson Avenue Interceptor.

Vasconcelos and Wright (2005) presented the results of an experimental investigation on the surges expected in a stormwater tunnel and noted different interactions between air and water phases during the filling process in which water was suddenly admitted into a pipe partially filled with stagnant water. The investigation identified various interactions between the air and water phases during the filling process, some of which related to the entrapment of discrete air pockets within the pressurized portion of the water flow. The movement of air in large bubbles in a pressurized flow exhibits characteristics that may limit the applicability of many numerical models that attempt to describe rapid filling processes in closed conduits. The typical assumption of hydrostatic pressure distributions will not hold at the strongly curved interface at the head of the moving air pocket, compromising numerical models based on the Saint-Venant equations. The structure of these interfaces resembles a gravity current front, as described by Benjamin (1968). In contrast, the trailing edge of the pocket may be described as a hydraulic bore often exhibiting a region in which a significant amount of entrained air develops a bubbly, stratified two-phase flow.

Literature searches have not yielded any experimental investigations in which the flow regime transition was generated by adding a surcharge inflow to an initially flowing system. Moreover, these searches have not located previous studies on the effect of the air phase in flow regime transition events in flowing sewers. Therefore, the objectives of this investigation were:

- to perform experimental measurements of flow regime transition events under circumstances with initial flow within the system; and
- to observe whether and how the air phase alters the system dynamics during the filling process.

The approach used in this investigation was to create flow surcharge by adding a sudden, large inflow in an experimental apparatus initially in a steady, gradually varied flow condition. The initial steady flow was generated by introducing an inflow from an upstream reservoir into a pipeline mounted within a variable slope flume. The downstream end of the pipeline was connected to an acrylic box with a sharp-crested weir that controlled the flow depth at the end of the pipe and created a gradually varied flow profile. During the experiment, a second inflow was suddenly admitted through a box located at an intermediate point along the pipeline by means of a two-way valve. This second inflow, larger than the initial steady flow, was selected such that a pipe-filling bore could be generated that propagated in both directions from the inflow point.

In the results presented in this chapter, the weir height was selected to provide an initial gradually varied flow backwater profile with the free surface slope less than the bed slope, and as a consequence, the depth increases in the direction of the flow. Due to this characteristic the ventilation in the pipe provided by the air-filled area at the pipe crown decreases in the direction of the flow. Vasconcelos and Wright (2005) have demonstrated that such conditions can result in air pressurization, which in turn result in air/water interactions during the surcharge of the pipeline. They provided a numerical method that was capable of accounting for the effect of the air pressurization on the water motion. However, other studies have indicated that other types of air-water interactions are possible.

Vasconcelos (2005) reports on a systematic investigation similar to that by Vasconcelos and Wright (2006) in which the effect of varying the location and degree of ventilation was examined. The investigation indicated a variety of different mechanisms by which air pockets could become entrapped in a rapidly filling system. These experiments were performed by initiating a sudden inflow at one end of a horizontal pipeline. Ventilation was provided only through one or more vertical shafts attached to the top of the pipeline at different locations and in which the ventilation could be restricted by placing small diameter orifices at the top of the shaft or by blocking the shaft completely. The addition of a gate at the downstream end of the pipeline prevented air escape through the surge riser. In an experiment in which sufficient ventilation is provided at the downstream end of the system, the conditions indicated in Figure 10.3 prevail; i.e. the advancing bore essentially behaves as a piston forcing the air out of the pipeline ahead of it.

Difference in initial conditions or other experimental configurations can result in entrapment of air pockets within the pressurized flow. A few of the different mechanisms are described below. One that may be more important in an initially flowing system is the shear flow instability mechanism as described by Hamam and McCorquodale (1982) and others. This air pocket entrapment mechanism, illustrated in Figure 10.4, results from waves generated by the velocity difference between the air and water phases. When the air-water interface is close to the pipe crown, the wave crests may contact the pipe crown creating a pressurized condition with air on either side; multiple air pockets can be created by this behavior over several wave crests.

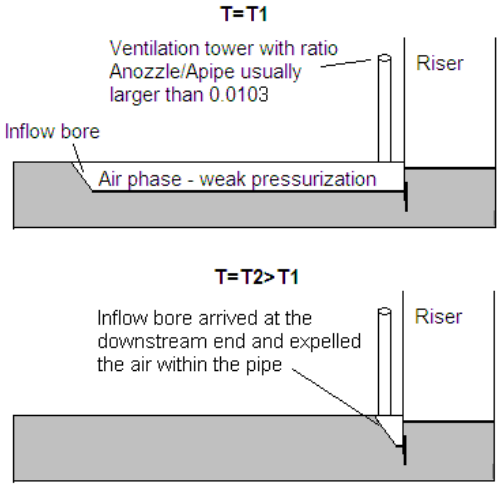

Figure 10.3 Adequate ventilation at downstream end of pipeline allows complete expulsion of air with no air pocket entrapment.

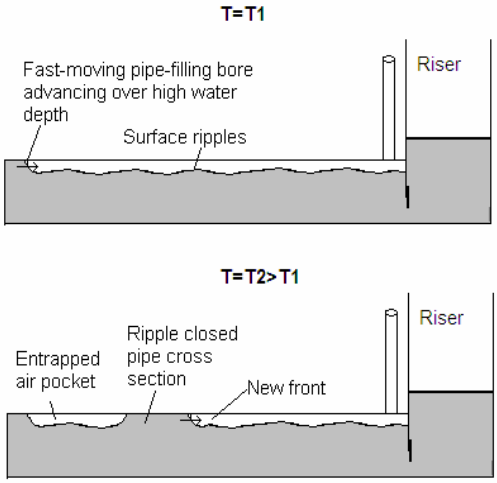

Figure 10.4 Air pocket entrapment due to the growth of shear flow instabilities.

Another air pocket entrapment mechanism is associated with adequate ventilation being placed at the wrong location such that the pipe-filling bore propagates against an increasing air phase pressure. Under the situation depicted in Figure 10.5, the air can be freely vented until the bore passes the ventilation location. Once past that point, the air is essentially trapped in the pipeline and becomes pressurized until it eventually begins to propagate upstream against the oncoming bore. The front of the upstream propagating air pocket resembles a gravity current as described by Benjamin (1968). Other mechanisms by which air pockets can be entrapped are described by Vasconcelos and Wright (2006).

10.2 Methodology

10.2.1 Experimental Apparatus and Experimental Variables

At the upstream end of the experimental apparatus, water was supplied into a large reservoir, with a cross-sectional area of 2.96 m^2. This water inflow was used to generate a steady gradually varied flow. The upstream reservoir was connected to a 94-mm diameter, 4.4-m long acrylic pipeline, mounted inside a variable slope flume. This pipeline, referred to as the upstream pipeline, ended in the middle inflow box (also mounted within the flume) with cross-sectional dimensions of 0.305 x 0.305 m and height 0.438 m above the pipeline crown. The second inflow was admitted at the middle inflow box through a two-way valve. The purpose of the two-way valve was to initiate a steady flow (to waste) in the supply pipeline that could be suddenly diverted into the inflow box by switching the valve. Finally, the middle inflow box was connected downstream to a 94 mm diameter, 10.4 m long acrylic pipeline which discharged into an acrylic weir box with cross sectional dimensions of 0.25 m x 0.25 m. The side of the weir box opposite to the pipe entrance had an opening 0.20 m wide in which a sharp crested weir with height 6.0 cm above the pipe invert was placed. Figure 10.6 presents a sketch of the experimental apparatus.

The measurement devices used in these experiments were:

- Piezo-resistive pressure transducer, manufactured by ENDEVCO, model 8510B-1, located in the pipe invert 12.8 m from the upstream reservoir;

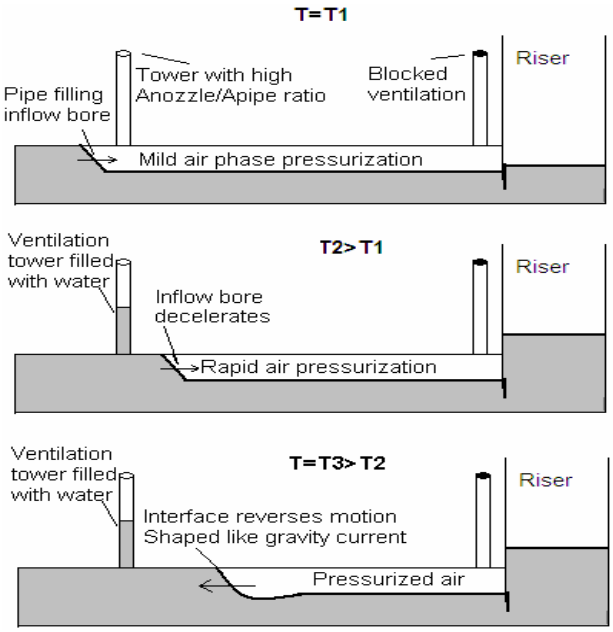

Figure 10.5 Air pocket entrapment due to misplaced ventilation.

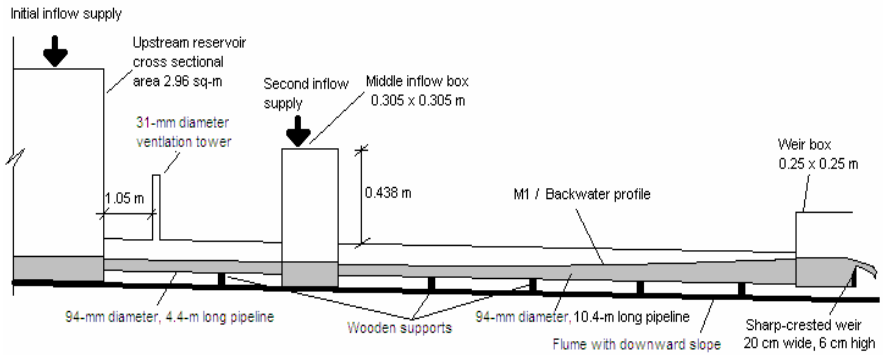

Figure 10.6 Sketch of the experimental apparatus used in the experiments with initial flow.

- Piezo-resistive pressure transducer, manufactured by ENDEVCO, model 8510B-1, located in the pipe crown 12.8 m from the upstream reservoir;
- Piezo-resistive pressure transducer, manufactured by ENDEVCO, model 8510B-1, located in the pipe crown 14.5 m from the upstream reservoir, close to the downstream pipeline exit;
- digital video recorder (30 frames per second) recording the water level variation of a 31-mm diameter stilling well mounted to the pipeline at the 12.7 m station and the inflow front advance between the 13.5 m and the 14.5 m stations;
- Acoustic Doppler velocimeter (ADV) probe manufactured by SONTEK, located at 12.9 m from the upstream reservoir.

The pressure transducers were calibrated during each experiment by comparing the transducer outputs to measurements of the static water level above them during steady flow conditions. Because all the pressure transducers were relatively close to each other, one stilling well was used in the experiments for the calibration of the transducers. Three experimental variables were systematically varied in the experiments: the initial inflow supplied at the upstream reservoir, the pipeline slope and the second inflow rate introduced in the middle inflow box. The range of the experimental variables used in the experiments is presented in Table 10.1. In total, eighteen different conditions were considered for this group of experiments.

Table 10.1 Model variables considered in the experiments.

Variable Name	*Range of values*
Initial upstream inflow (L/s)	1.0, 2.0 and 3.0
Flume slope (%)	0.5 and 0.3
Second inflow admitted at middle box (L/s)	6.0, 9.0 and 12.0

10.2.2 Experimental Procedure

The procedure used in the experiments is summarized as follows:

1. After the required flume slope was set, the desired initial upstream inflow rate was admitted in the system, and

sufficient time was allowed for steady flow conditions to develop.

2. After steady flow conditions were established, the downstream video recorder was started. This camera was used to determine the timing of the events during the experimental runs.
3. In sequence, the ADV probe, the upstream video recorder and the pressure transducers were started.
4. With all the measuring devices operating, the second inflow was admitted through the middle box by manually switching a two-way valve. Two inflow fronts were generated by the second inflow, propagating upstream and downstream from the middle box.
5. The pressure transducers stopped 40 seconds after the start-up. The ADV probe recorded the flow velocity up to 60 seconds after the start. Both pressures and velocities were sampled with 50 Hz frequency.
6. The cameras were stopped manually. The difference in the initial and final readings at a stilling well nearby the transducer location was used in the calibration of the transducer outputs.

This switching time of the two-way valve controlling the second inflow was usually less than one second. At least three repetitions of each experimental run were performed to verify consistency of the measurements and to reduce the uncertainty caused by the different opening times of this valve. An unanticipated feature of the apparatus was the air entrainment, sometimes significant, on the introduction of the second inflow at the middle inflow box. This entrainment resulted in the admission of small air bubbles to the pipelines. A ventilation tower was installed in the pipeline upstream of the second inflow box in order to vent the air bubbles accumulating there. In general, the volume of these entrained air bubbles was small with respect to the volume entrapped during the pipe-filling process.

10.3 Experimental Results

The outcome of the experimental runs depended greatly on the degree of ventilation in the system, which in turn depended on the flow depth at the weir box exit. The initial weir head was a function of the upstream inflow

rate, and the Kindsvater-Carter equation is used to calculate the theoretical weir head h_{weir} (Brater et al., 1996):

$$Q = \frac{2}{3} C_e \sqrt{2g} (B_{weir} + K_b)(h_{weir} + K_h)^{3/2} \tag{10.1}$$

In the above equation, Q_{weir} was set to the upstream inflow rate; C_e is dependent on the geometry of the weir, and for the case of this experiment is given by $C_e = 0.593 + (h_{weir}/0.11)$ with h_{weir} in meters; K_b is also dependent on the weir geometry, and for the case of the experiments is given by $K_b = 0.0035$ mm; and K_h is a constant parameter, equal to 0.001 m. As the upstream flow is set to 1.0, 2.0 and 3.0 L/s, the calculated values for h_{weir} are 1.9 mm, 3.0 mm and 4.0 mm respectively.

These different weir heads impact directly on the amount of ventilation available for the air to escape at the weir box. For the smallest upstream inflow, the resulting depth at the downstream end of the pipeline was such that the ventilation conditions were adequate, and no signs of air pressurization were recorded. As Figure 10.7 indicates, for the case with the pipeline slope of 0.3%, upstream inflow of 1.0 L/s, and the second inflow of 9.0 L/s, a variation of the pressures recorded with the transducers and the velocity recorded with the ADV occurred after when the inflow front passed by the measurement station. For the intermediate upstream inflow (2.0 L/s) free surface flow conditions were still present throughout the downstream pipeline prior to the second inflow admission. However, the resulting ventilation area was significantly smaller, and it was anticipated that such conditions could lead to air pressurization as the second inflow was admitted to the system. This was confirmed by the experiments, and the resulting flow behavior was rather complex. Figure 10.8 presents a sketch depicting the typical outcome for these experimental conditions. Immediately after the second inflow was admitted, the hydraulic bores pushed the air phase outwards away from the second inflow box creating air pressurization. The small ventilation area at the downstream end of the pipeline resulted in a large air phase velocity and the relative velocity between air and water phases was large enough to create waves on the surface of the water. Eventually the waves touched the pipe crown, closing the ventilation in the pipeline, resulting in the entrapment of an air pocket that was then pushed downstream by the inflow.

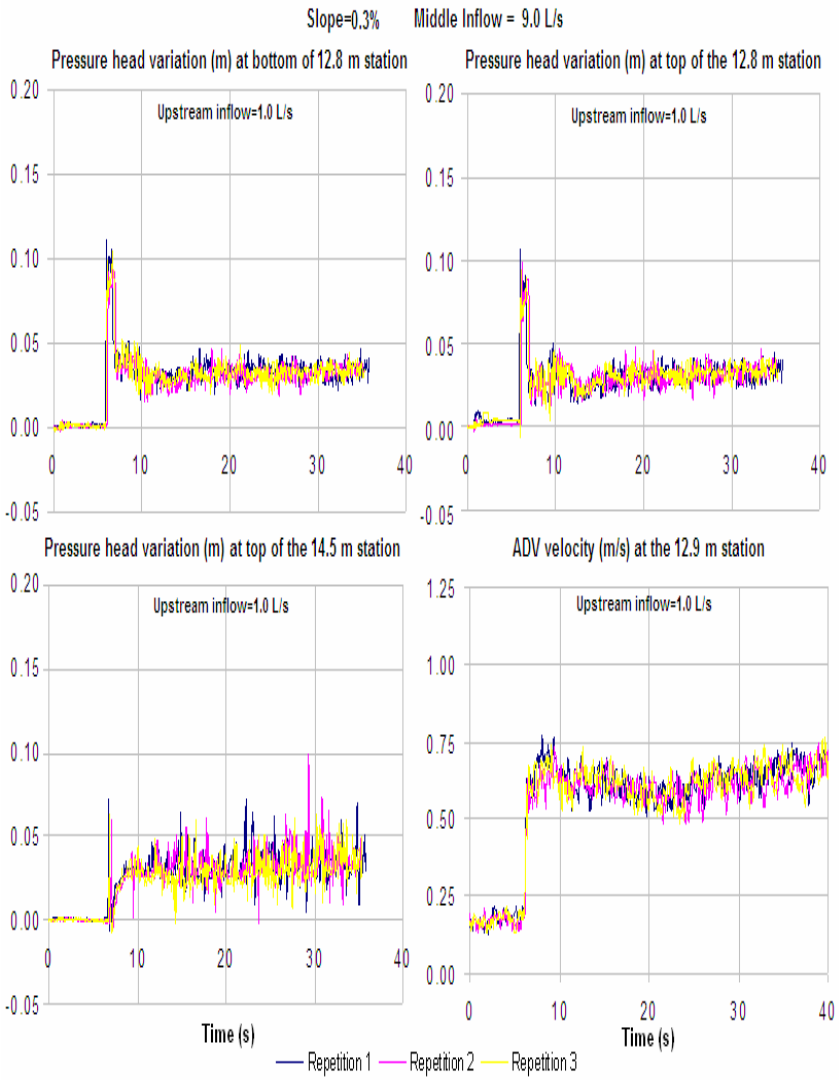

Figure 10.7 Experimental results for flume slope of 0.3%, second inflow 9.0 L/s and initial upstream inflow of 1.0 L/s.

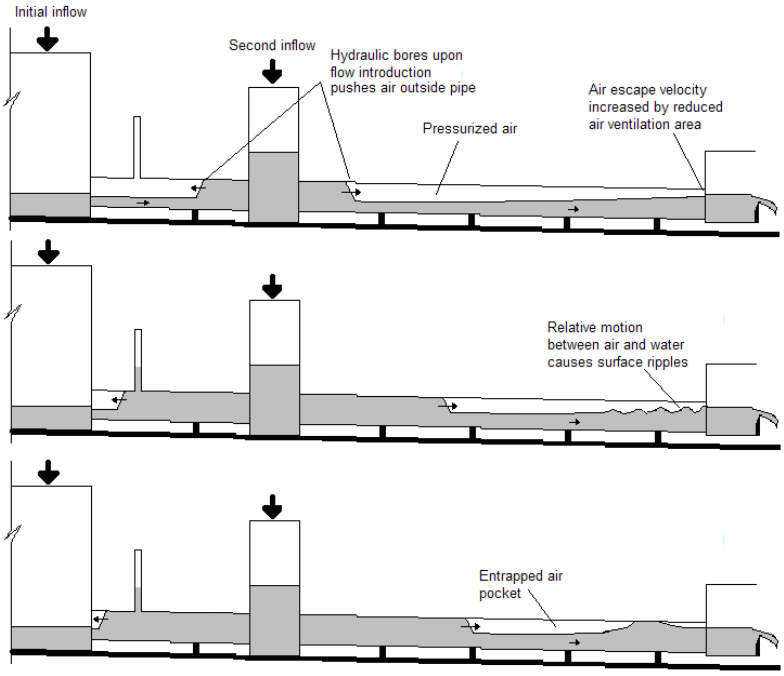

Figure 10.8 Sketch of flow configuration for the cases when the initial upstream inflow was 2.0 L/s

Figure 10.9 presents experimental results for the case where the pipeline slope was 0.3%, the second inflow was 9.0 L/s, and the upstream inflow was 2.0 L/s. The results for these conditions indicate a brief period in which there is a gradual increase of the pressure resulting from the pressurization of the air phase. Following this, pressure spikes were recorded as the air pocket became entrapped, which was followed by a sudden pressure decrease, probably resulting from the release of the air pocket as it reached the weir box. The second group of pressure peaks observed were related to the arrival of the inflow front at the transducer stations. The velocity recorded by the ADV indicates a gradual increase of the flow velocity during the initial 5 seconds after the inflow was admitted in the pipeline. This increase in the velocity may be explained by the rise of the air phase pressure, in a similar fashion as the pre-bore motion feature described by Vasconcelos and Wright (2003). The inflow front arrived at 5 seconds, creating a sudden increase of

the velocity. For the experimental runs when the upstream inflow rate was 3.0 L/s, there was an absence of ventilation at the downstream end of the pipeline due to the weir head, and as a result the downstream portion of the pipeline flowed in pressurized conditions.

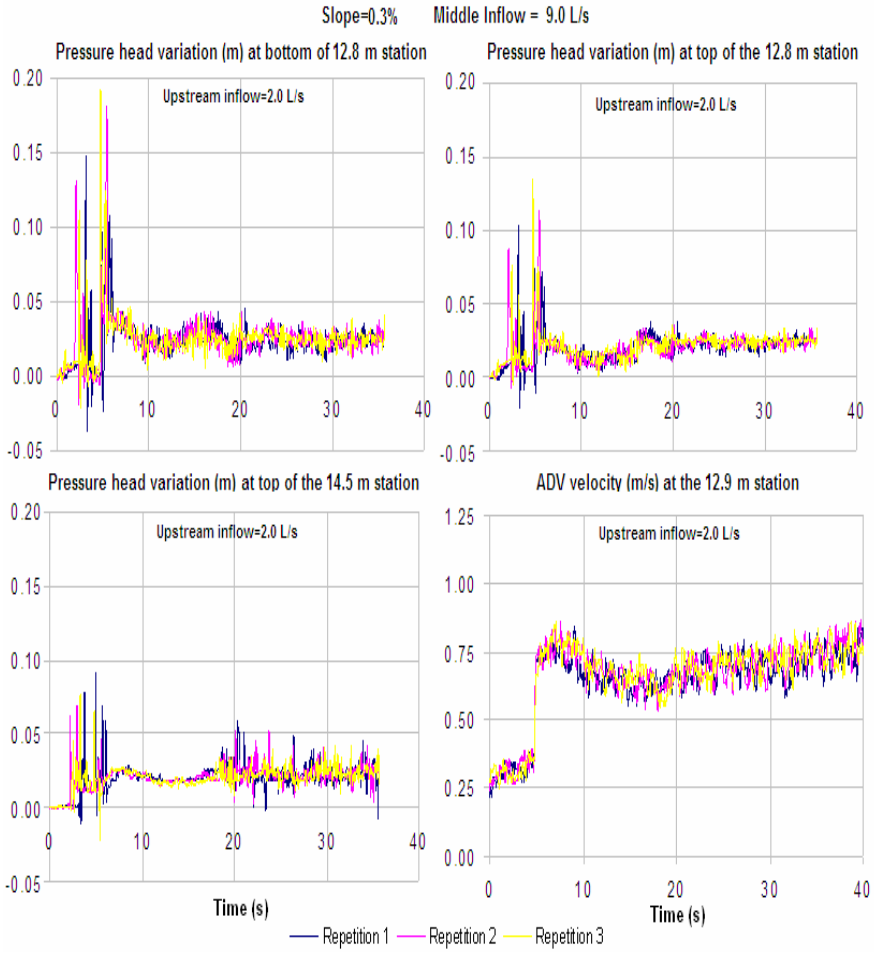

Figure 10.9 Experimental results for a flume slope of 0.3%, second inflow of 9.0 L/s and initial upstream inflow of 2.0 L/s.

As Figure 10.10 illustrates, the wedge of air located at the pipe crown of the downstream pipeline immediately became entrapped and pressurized following the inflow introduction. As the inflow pushed the air downstream, the shape of the wedge evolved into a series of gravity current-shaped fronts. These pockets were pushed downstream and were expelled at the weir box exit in the form of smaller bubbles. In general, since the downstream end of the pipeline was initially flowing in a pressurized regime, the introduction of the second inflow resulted instantly in a condition whereby the entire downstream pipeline became pressurized.

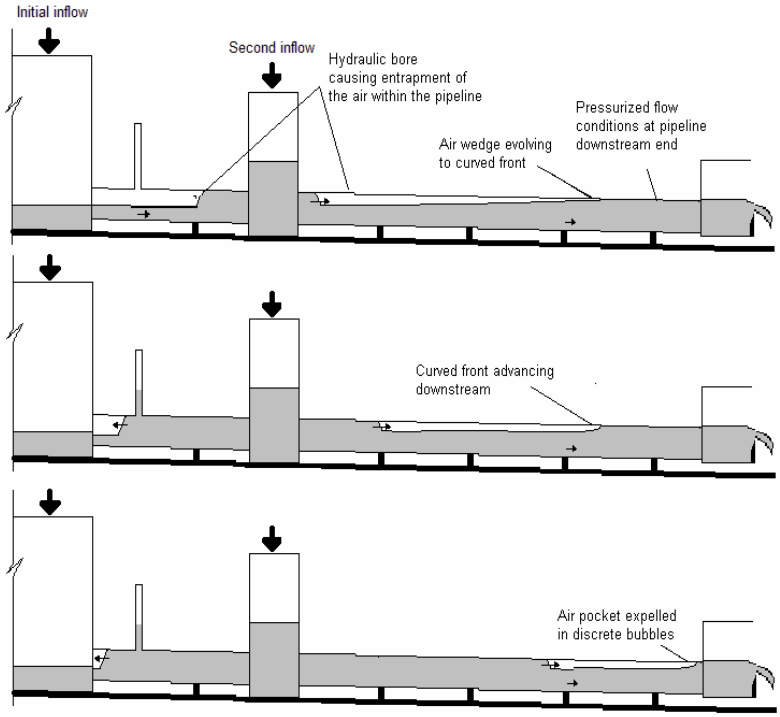

Figure 10.10 Sketch of flow configuration for the cases when the initial upstream inflow was 3.0 L/s

This is confirmed by the experimental results, presented in Figure 10.11, for the case where the pipeline slope was 0.3%, the second inflow was 9.0 L/s and the upstream inflow was 3.0 L/s. As the second inflow is

admitted, both the velocity and pressure measurements indicate a sudden increase as would be the case if the pipeline was flowing full. Pressure spikes were recorded, particularly by the transducer located at the 14.5-m station, and those were associated with the expulsion of air bubbles at the weir box. Unlike the previous velocity measurements, there were no jumps in the velocity caused by the inflow front arrival. This is similar to the condition in which a second flow is admitted to a pipeline already flowing full. The arrival of the inflow front is no longer clearly identifiable. Instead, the sudden decrease of the velocity recorded by the ADV is caused by the passage of the air pocket at the ADV probe station.

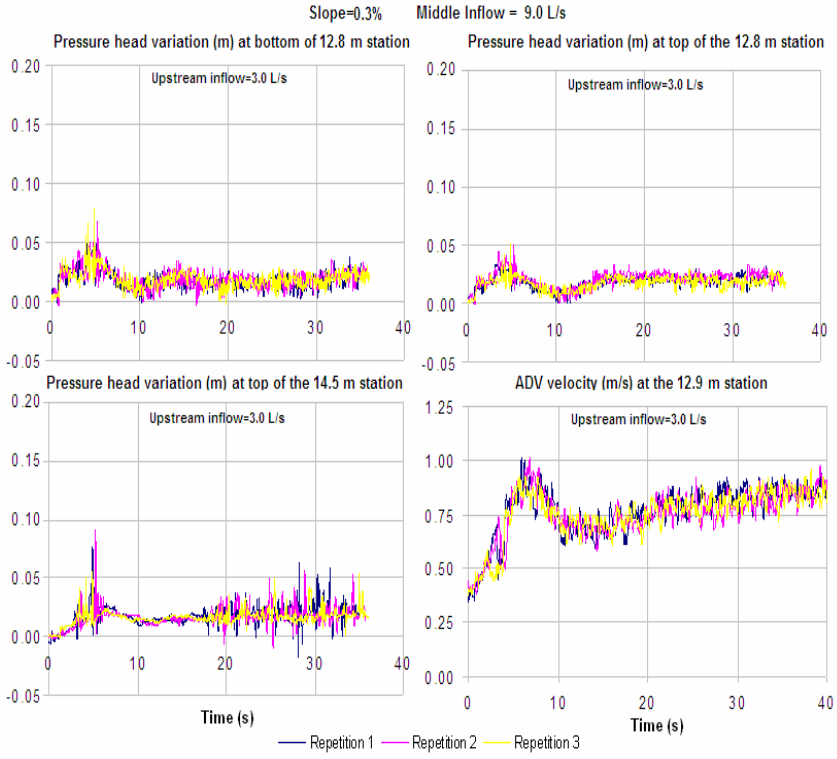

Figure 10.11 Experimental results for the flume slope of 0.3%, second inflow of 9.0 L/s, and initial upstream inflow of 3.0 L/s.

The experimental results obtained with the second inflow rates of 6.0 and 12.0 L/s indicated no qualitative change in the experimental results. For the case when the second inflow was 6.0 L/s, the pressure rise caused by the air phase pressurization was less pronounced, and features such as the Pre-bore motion were less clearly indicated. For the case when the second inflow was 12.0 L/s, the pressure rise was more pronounced, as were the pressure peaks as the air pockets formed and were expelled. These results are not shown in this chapter; the complete set of results is presented in Vasconcelos (2005). Generally, the complete set of data indicates that the gain in the flow velocity caused by the pre-bore Motion and pressure rise increased with the second inflow rate.

The results obtained with the slope of 0.5% were also qualitatively similar to the correspondent ones with the 0.3% slope. In these conditions, however, the initial amount of air within the downstream pipeline prior to the second inflow admission was higher, causing an exacerbation of the air phase pressurization effects, such as stronger pressure peaks upon the expulsion of air pockets and more pronounced Pre-bore Motion. Also, for the case when the initial upstream inflow was set to 3.0 L/s, the portion of the pipeline initially in pressurized flow conditions was smaller than the case when the slope was 0.3%.

10.4 Conclusions

The experiments described in this chapter are believed to be the first that study the flow regime transition problem by introducing inflow into a pipeline at two different locations, a condition more representative of typical stormwater collection systems with multiple inflow points. The experiments were performed by introducing a steady water inflow at the upstream end of the apparatus, creating a gradually varied flow condition, and then suddenly admitting a second and larger inflow at an intermediate point of the pipeline. Measurements with pressure transducers and the ADV probe were performed along with the recording of the inflow advance with the digital video recorder.

The experiments were based on the creation of backwater flow profiles that reduced the area through which air could be ventilated through the downstream end of the pipeline. When the upstream inflow rate was 2.0 or 3.0 L/s, the resulting ventilation area at the weir box was small or absent and the introduction of the second inflow rate resulted in air phase

pressurization. No signs of air pressurization were detected when the upstream inflow rate was set to 1.0 L/s as the ventilation area above the free surface was sufficiently large throughout the free surface portion of the flow.

For the case with the upstream inflow equal to 2.0 L/s the depth of the flow and the head at the weir increased. In this condition, the downstream propagating inflow front blew air over the free surface flow and created waves that increased in amplitude, contacted the crown of the pipe, and caused the entrapment of air pockets. Pressure peaks were recorded as these pockets were eliminated through the weir box exit.

For the case of 3.0 L/s, the introduction of the second inflow resulted in immediate pressurization of the pipeline, similar to the case of inflow admission into an already filled pipeline. The release of the air pockets caused some pressure peaks, but the passage of the inflow front was no longer identifiable in the results.

The general conclusions of these experiments are that care in numerical modeling of the flow regime transition must be taken in cases where air phase pressurization and air pocket formation are possible. Model approaches based on the solution of the Saint-Venant equations can be modified to incorporate the air phase pressure and thus handle mild air pressurization conditions. In cases when air pockets are formed, a different approach that does not depend on the shallow water flow assumptions is required to accurately model the flow. The magnitude of the errors that could be introduced by using numerical methods that assume hydrostatic pressure variations remains to be demonstrated.

These experiments also demonstrated that the mechanisms for air pressurization in flowing sewers are similar to the experiments performed by Vasconcelos (2005) with an apparatus initially in stagnant conditions. Features such as the pre-bore motion were detected as was the development of shear flow instabilities. This outcome suggests that simpler experiments such as those performed by introducing an inflow into a system initially at rest can provide important insight into the general problem of rapid filling of initially flowing sewers.

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