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Mechanisms for Stormwater Surges in Vertical Shafts

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A number of large scale combined sewer systems have experienced events in which surges have resulted in the return of poor quality stormwater to grade in what are referred to as geysers. In spite of current concerns that these events be avoided by the proper design of new systems, there have been limited investigations to understand the conditions that lead to these surges or how to avoid them. In the course of an ongoing investigation into the dynamics of rapidly filling pipelines, two phenomena have been identified that may result in geyser-like phenomena. Both of these are associated with the movement of a large pocket of entrapped air along the crown of a nearly horizontal pipe. One case occurs when the leading edge of the air cavity arrives at a vertical riser at a location along the pipeline that is already in a surcharged state. A second case occurs as the trailing edge of the same air pocket arrives at the riser and the pipe is not in a surcharged condition. Experiments have been performed to reproduce both of these situations in a simplified fashion where several of the key variables can be controlled. The features of these experiments are described as well as some of the results obtained to date. These results are interpreted to identify aspects of a storage tunnel system that are under design control and how these affect the magnitude of the observed surges. Finally, since the experiments are performed in a relatively small-scale apparatus, speculation is presented on

Wright, S.J., J. Lewis and J. Vasconcelos. 2007. "Mechanisms for Stormwater Surges in Vertical Shafts." *Journal of Water Management Modeling* R227-05. doi: 10.14796/JWMM.R227-05.
© CHI 2007 www.chijournal.org ISSN: 2292-6062 (Formerly in Contemporary Modeling of Urban Water Systems. ISBN: 0-9736716-3-7)

the scale effects of a reduced scale apparatus, and conclusions regarding the applicability of the observed results to prototype applications are made.

5.1 Introduction

A number of large scale stormwater collection systems have experienced a phenomenon referred to as *geysering*. Figure 5.1 is an image of a geysering event taken from a video obtained by the Minnesota Department of Transportation in the median of Interstate 35 in the vicinity of Minneapolis. Based on objects in the video, it appears that this geyser erupting from a manhole extends some 20-30 m into the air. The complete video shows two such events within a few minutes of each other and significant flooding of the roadway. Similar phenomena have been reported in other systems including a photograph presented in Guo and Song (1991). There seems to be little general appreciation for the significance of this phenomenon and little consideration is taken in the design of stormwater collection or storage facilities to avoid these events; nor does there appear to be any significant research into the causes, or the necessary steps to minimize their occurrence. Although Guo and Song (1991) present an image of a geyser, their analysis is unrelated to the phenomenon. The appearance in the video, from which Figure 5.1 was extracted, suggests the geyser comprises a mixture of air and water, implying that trapped air in the flow in a nearly horizontal sewer may play an important role in the geysering process. The authors have been involved in a variety of studies related to transients in rapidly filling pipelines (e.g. Wright, et al, 2003, Vasconcelos and Wright, 2003 and Vasconcelos and Wright, 2005) and have performed a variety of laboratory experiments that shed some light on this phenomenon. This chapter presents the results of some of these studies. We describe the qualitative observations that have led to more detailed experiments, the results of these additional experiments, and an interpretation of these results in light of our understanding of the geysering process. Results of these experiments are presented to identify the key variables that lead to the formation of geyser-like events. The experiments have been performed in a relatively small scale apparatus so it is unlikely that the observation in this model can be directly scaled to the prototype occurrence indicated in Figure 5.1. Indeed, the qualitative nature of the laboratory generated geysers is different than the one in the figure. The nature of two-phase flows is invoked to explain the difference between the model and prototype observations.

Figure 5.1 Image of geyser from a stormwater tunnel in the median of I-35 taken by the Minnesota Department of Transportation.

5.2 Background

Most large-scale stormwater storage tunnels involve a nearly horizontal conduit with vertical inflow through a number of discrete points. The tunnel is generally designed to retain the inflow for a specified precipitation event, typically one with a return period on the order of 5-10 years. If the design precipitation is exceeded, the tunnel will undergo a transition from a free surface to a pressurized state. It is during this flow-regime transition that significant surges may occur in the pipeline. The transition may occur as a hydraulic bore if the filling process is sufficiently rapid and the bore may propagate in both directions along the pipeline. It is noted that a hydraulic bore does not necessarily result in a flow regime transition; however the resulting free surface bore could itself lead to a flow-regime transition after reflection off an end of the pipeline or other geometric transition. If the pipe-filling bore propagates along a horizontal pipeline and no other flow-regime transitions occur due to inflow at other locations, air can be displaced

from the pipeline through whatever ventilation points might be available with negligible pressurization of the air. A number of deviations from this described condition may lead to significant air pressurization including (i) restricted ventilation points from which air can escape; (ii) complicated system geometry in which air may become trapped at high points along the pipeline; and (iii) complex filling scenarios in which reflected waves or flow regime transitions at multiple locations trap air within the pipeline. Because of the multitude of different circumstances that can lead to air entrapment, it is difficult to specify events that may be critical to design detail to avoid these effects.

In an attempt to gain some insight into relevant phenomena that might be important in the design of stormwater storage tunnels, a simplified laboratory model was constructed which aimed to reproduce the essential elements of flow in a rapidly filling stormwater conduit. The initial study conducted was simply to determine the necessary conditions required to obtain large surges in vertical shafts at one end of a nearly horizontal pipeline (Wright, et al, 2003) but the basic apparatus has been modified several times for continuing investigations into various phenomena that have been observed during different phases of the testing. The original apparatus consisted of a 14.5 m long, 9.4 cm-diameter acrylic pipeline installed within an adjustable slope flume. Filling was accomplished by the sudden initiation of inflow through a fill box attached to one end of the pipe such that it would overflow once the water reached a height of approximately 0.14 m above the pipe crown. A 19 cm-diameter surge riser was mounted at the opposite end of the pipeline. The pipeline was initially filled with a fixed volume of water, allowed to come to stagnant conditions, and then a sudden inflow was initiated into the fill box. During the course of performing experiments to measure the magnitude of surges generated in the surge chamber as a function of variables such as the inflow rate, pipe slope and initial water level, it was observed that it was possible to generate a number of different flow conditions in which air became entrapped in the nearly horizontal pipeline. These observations led to a variety of related experiments in which different modifications were made to the original apparatus in order to make additional observations on the role of the trapped air on flow behavior. One such modification was the installation of small diameter (32 mm) vertical risers with a height of 0.45 m to provide ventilation at several points along the pipeline. Experiments with the ventilation risers installed demonstrated that it was quite easy to establish flow conditions that would result in water surging up over the tops of the risers. Indeed, with a little experimentation, it was possible to generate geysers propelling water to a sufficient height

(approximately 4-5 m) so that it impinged on the laboratory ceiling. The conditions that resulted in the largest surges through the ventilation riser were associated with the migration of a large, discrete air pocket along the crown of the nearly horizontal pipeline. It was observed that two large surges could occur under this flow condition. The first was associated with the arrival of the air pocket at a vertical riser that was partially filled with water due to the existence of pressurized conditions at that location. The second large surge occurred at the arrival of the trailing edge of the air pocket at the riser, which at that instant, was totally evacuated of water. The magnitude of either surge could be quite significant and it was decided to perform additional experiments to investigate both phenomena in more detail so that an understanding of the key flow processes controlling the magnitude of the surges could be developed. Two separate experimental setups were developed for this purpose. Both setups are described below along with the preliminary results from the experiments.

The propagation of a large, discrete air pocket is a special case of the type of flow that is referred to in the two-phase flow literature as *slug flow*. The air pocket is not symmetrical and has a distinct head and tail as depicted in Figure 5.2. The head of the air pocket (Figure 5.2a) exhibits a distinct front with significant curvature and a non-hydrostatic pressure distribution; the propagation of such a front was analyzed by Benjamin (1968). In contrast, the tail of an air pocket resembles a hydraulic bore (Figure 5.2b).

A feature of the Benjamin solution to the air intrusion problem is that even if the pressure within the air pocket was atmospheric, the pressure within the fluid ahead of the intrusion would be greater than the air pressure. If the air within the pocket becomes pressurized, then the pressure in the fluid ahead of the intrusion would be even higher. Pressure waves in the filled portion of the pipeline propagate much more rapidly than the intrusion itself creating a pressure within the water that would be sufficient to cause water to rise in any vertical shafts that are connected to the pipeline. As the air pocket arrives at this shaft, the air begins to rise in the vertical shaft due to its buoyancy and provides a force that tends to displace the water upwards in the shaft. Davies and Taylor (1950) have provided an analysis for the special case of an air bubble rising in a vertical pipe that is capped on the top. In this situation, the water that is displaced by the air must be forced as a return flow along the perimeter of the rising bubble. If the vertical shaft is not capped, then an increase in the free surface location within the shaft would occur due to the increased pressure in the rising bubble. In an extreme case, a surge in the water standing in the shaft prior to the bubble arrival could be created.

For a discrete air pocket, the trailing end of the pocket would involve a return to a pressurized flow state in a jump-like transition. Assuming that the trailing end is propagating at a nearly constant celerity, steady continuity and momentum equations could be written in a frame of reference of the jump and the pressure on the pressurized side of the jump could in principle be solved for. As this jump reaches a vertical shaft that is assumed to have been evacuated of water due to the size of the air pocket allowing sufficient drainage of the initial water in the shaft, the return to a pressurized state will cause water to rise in the shaft in the form of a transient surge. Observations indicate a fair amount of air entrainment into the jump and it is conceivable that the reduced density of the air-water mixture rising into the shaft could result in an increased surge height. It is important to understand the relative significance of these described processes or other related phenomena, not only to be able to define critical conditions for design, but also to determine appropriate methods for the analysis of resulting surges.

(a.) Head of moving air pocket in a horizontal pipeline.

(b.) Tail of moving air pocket in a horizontal pipeline.

Figure 5.2 Characteristics of propagating air pocket.

5.3 Experimental Investigations

5.3.1 Geysering Associated with Head of Air Pocket

As the head of an air pocket reaches a vertical riser that is partially filled with water, buoyancy forces cause the air to begin to rise in the vertical shaft. As the air rises, the water in the shaft either (i) flows downwards as a film flow around the perimeter of the rising air bubble, or (ii) is forced upwards by the rising air bubble beneath it. Most previous analyses of this situation have related to air intrusion into the bottom of a filled vertical pipe closed at the top such that no upward migration of water is permitted; see, for example, Davies and Taylor (1950). This type of experiment is performed by opening the bottom of a vertical pipe that is initially filled with water, in which case the water drains from the pipe around the air that is filling the pipe. For conditions in which surface tension has a negligible influence on the air intrusion, the bubble rise velocity U_i is given by the Davies and Taylor analysis as equal to $0.35 (gD)^{1/2}$ with D being the diameter. In the case where vertical motion is allowed as in the partially filled riser shaft open at the top, a process that could be referred to as geysering will occur when the film flow around the Taylor bubble is insufficient to prevent the remaining water from rising to the top of the shaft. A number of variables will control this occurrence including the diameter of the vertical shaft, the initial pressure in the air pocket, and the shaft height.

The experimental apparatus depicted schematically in Figure 5.3 was used to investigate the rise of the fluid in a shaft partially filled with water subject to the intrusion of a large air bubble at the bottom (large in this context implies that a Taylor bubble with length considerably greater than the shaft diameter). The apparatus was constructed of approximately 4 m of horizontal 9.4 cm-diameter acrylic pipe. A quarter-turn butterfly valve was installed 0.55 m from one end and air was introduced under pressure in to short side of the pipe. The opposite side of the pipe was filled with water to provide a specified water level in the 0.61 m high vertical shaft installed 0.49 m from the far end of the pipe. The experiment was initiated by suddenly opening the butterfly valve, initiating an air bubble intrusion into the liquid-filled portion of the pipeline with a shape similar to that depicted in Figure 5.2a. The air and water pressures were not the same on either side of the butterfly valve prior to opening and an inertial oscillation was set up in the shaft as the water level adjusted to balance the pressures as the bubble was propagating along the pipeline towards the shaft. The magnitude of

these oscillations depended on the difference in initial pressures but in most cases, they were fairly well damped out prior to the arrival of the air. Once the air intrusion arrived at the shaft, it formed a Taylor bubble with the behavior described above. Figure 5.4 shows a sequential set of images obtained from a video of the rising Taylor bubble; initially the cap of the bubble is slightly asymmetric due to the nature of the entering air, but after a short distance, it evolves into a symmetrical configuration.

Figure 5.3 Schematic of experimental setup to investigate surges at head of trapped air pocket.

Figure 5.4 Sequence of images from Taylor bubble rising in vertical shaft (air bubble propagates from left to right in horizontal pipe). There is approximately 0.14 s time interval between successive images.

Three different experimental variables were selected to vary the conditions to observe when water might be expelled from the top of the vertical shaft. These were the shaft diameter, the initial air phase pressure and the initial water height in the shaft; these latter two were measured prior to the opening of the butterfly valve. Four different shaft diameters were considered: 12.7, 25.4, 44.4 and 57.1 mm. The initial air phase pressure head was set at either 0.303, 0.61 or 0.915 m while the initial water level in the vertical shaft was set at either 0.254, 0.356 or 0.457 m.

Various experimental measurements were made related to the rise of the air and water within the vertical shaft. A piezo-resistive pressure transducer, Endevco model 8510B-1, was installed at the invert of the horizontal pipe 1.9 m upstream of the vertical shaft; dynamic pressure measurements during the duration of the experiment were obtained. Additional measurements were obtained from a digital video recording of the motion within the shaft. These images could be analyzed on a frame-by-frame basis to measure the location of both the free surface and the air bubble-water column interface. Velocities of both interfaces were obtained from the time displacement history of each. For each of the 36 combinations of experimental conditions, three repetitions were made in order to ensure that consistent experimental results were obtained.

5.3.2 Geysering at Tail of Air Pocket

Preliminary observations of the surges in a vertical shaft upon the arrival of the tail of an air pocket seemed to provide a consistent view of the conditions required to develop large surges. First of all, a strong bore would result in the greater entrainment of air into the liquid following the air pocket. It is conceivable that the lower density of the resulting air-water mixture provides a mechanism to generate larger surges in the vertical shaft. Also, the magnitude of the surge would generally be related to the strength of the hydraulic bore. The initial pipe-filling bore would not result in a geyser event. This can be explained as due to the fact that in the experimental apparatus, the fill box was not completely filled by the inflow by the time the bore arrived at the riser. This implies that the pressure head behind the initial bore is not too large, resulting in a small driving force for the subsequent surge in the vertical riser. However, after the bore reflected off the far end of the pipeline and a significant surge was generated in the surge riser at that end, the returning air pocket would be under much greater pressure and a much stronger surge would be observed in the ventilation riser. Although the maximum pressure heads in the surge riser might not be

sufficient to force water to the top of the ventilation riser under hydrostatic conditions, both the inertia of the water rising in the ventilation riser and the lower density of the air-water mixture in the riser could be sufficient to contribute to a developing spilling condition. Additional experiments were conducted to assess the relative importance of these two phenomena. The importance of understanding the relative contributions is that the inertial rise in the ventilation shaft should be capable of being predicted with a numerical model that describes the air and water as separate phases; in contrast if the air entrained at the tail of the air pocket is important to the surge process, a full two-phase flow model formulation will be required.

Figure 5.5 is a schematic of the experimental setup. The purpose of the setup was to easily create and monitor a pipe-filling hydraulic bore propagating along a horizontal pipeline and passing by a vertical riser shaft. As shown in Figure 5.5, the pressure head is provided by a constant-head, overflow reservoir. A weir installed in a box at the downstream end of the pipeline was used to establish an initial depth within the pipeline. A quarter-turn butterfly valve allowed for quick release of the pressure surge from the constant head reservoir. The main pipeline was 7.6 m in length from the valve to the outlet and constructed of 9.4 cm diameter clear acrylic pipe. Piezo-resistive pressure transducers, Endevco model 8510B-1, were located 0.81 m upstream and 0.94 m downstream from the vertical riser as well as one within the riser itself (near the bottom). This allowed for complete monitoring of the pressure surge interaction between the pipeline and riser.

Figure 5.5 Schematic of experimental setup to simulate surges at trailing edge of trapped air pockets.

In order to understand the interactions between the different aspects of the system, four variables were systematically adjusted. The weir box at the downstream outlet was used to regulate the initial depth of the system for the

three values of 50%, 70%, and 95% full with respect to pipe diameter. All of these risers were approximately 2 m in length; this length was chosen so that all liquid entering the riser would be contained within it in contrast to the previously described experiments in which surges often overflowed the riser. Three diameters for the vertical riser were used, namely 12.7, 25.4 and 44.4 mm. The ventilation of the vertical riser was adjusted to be fully open, fully closed, or roughly 5% open by area. The partially open case was established with a plug in which a rounded nozzle was installed at the top of the riser; a similar plug with no nozzle was installed at the top of the pipe to establish the fully blocked condition. The last variable, reservoir elevation, was established by raising or lowering the supply reservoir such that the distance between the free surface of the reservoir and the invert elevation of the horizontal pipe was 0.822 m, 0.703 m, or 0.627 m. With three possibilities for each of the four variables, a total of 81 combinations were evaluated experimentally.

Each of the 81 experimental combinations was repeated three times to improve confidence in the results. The system was allowed to reach a steady state flow before the valve was gradually closed. This allowed the water surface in the horizontal pipeline to drain down to a stagnant condition with an initial water surface equal to the downstream weir height. Then the valve was rapidly opened to create a pressure surge in the form of a pipe filling hydraulic bore. The piezo-resistive pressure transducers convert the change of pressure to a voltage output which is sent to a data acquisition system (National Instruments DAQPad MIO-16XE-50) and then to a computer. Each trial was calibrated with the initial and steady state readings from a stilling well located at the base of the main pipe near the vertical riser.

5.4 Results and Discussion

5.4.1 Effects of System Variables

Surges at Head of Air Pocket

Results are presented in a normalized format. The dimensionless parameters are as follows:

- The vertical shaft diameter is non-dimensionalized by the pipe diameter of 9.4 cm to form a dimensionless tower diameter D_t^* ;

- All vertical dimensions are non-dimensionalized by the height L of the shaft so that a value Z_{rel}^* of 1.0 implies that the relevant interface has reached the top of the shaft;
- Dimensionless air pressure head is defined as $H_{air}^* = H_{air}/L$;
- All velocities are non-dimensionalized by $(gD)^{1/2}$ where D is the pipe diameter; in this fashion the computed interface velocities V_{int}^* can be compared to the rise velocity of a Taylor bubble in a capped pipe;
- Dimensionless time $T_{rel}^* = t(gD)^{1/2}/L$.

Only the results of a few representative experiments are presented in this chapter; all experimental results are presented in Vasconcelos (2005).

Each of the variables that were controlled in the experiments could be observed to have a systematic influence on the experimental results. It is difficult to isolate the effects of the initial air pressure and the initial water depth in the vertical shaft since these changed upon the opening of the butterfly valve in consistent and intuitive ways. For example, if the air pressure exceeded the hydrostatic pressure within the shaft, the water level would rise in the shaft until a pressure equilibrium was established, conversely a lower air pressure could result in a drop in the water level in the shaft. If the changes in water level were significant, inertial oscillations would be observed in the pressure transducer output. However, these oscillations were largely damped out by the time that the air bubble arrived at the riser shaft.

To obtain a more accurate view of the interaction between these two variables, a quantity defined as *relative surge* was computed, only for the two largest shaft diameters since the surge was not contained within the riser for most of the two smaller shaft diameters. Relative surge was defined as the maximum rise of the water surface within the shaft compared to an estimated equilibrium water surface level developed during the propagation of the air bubble within the horizontal pipe. The results of these computations are presented in Figure 5.6. Results for the smallest shaft diameter (12.7 mm) are not presented since every one of those resulted in water spilling at the top of the shaft; only three experiments did not spill for the shaft diameter of 25.4 mm. The data for various experiments are presented as a function of the initial air pressure head as this would be a measure of the driving force on the air bubble. The different initial water levels in the shaft are included in the data. The air pressure head does not appear to have a noticeable impact on the magnitude of the relative surge, not does the initial shaft water level. Only the riser diameter seems to have a significant effect.

Figure 5.6 Variation of relative surge as a function of air pressure head for various tower diameters.

The most important variable in determining the magnitude of the surge in the vertical shaft was the riser diameter. This can be seen by comparing bubble rise velocity for representative experiments with the largest and smallest shaft diameters; these results are presented in Figure 5.7. For the largest shaft diameter, the water surface interface scarcely changes during the bubble rise and the air–water interface and the non-dimensional vertical rise velocity of the bubble very nearly matches the value of 0.35 suggested for a Taylor bubble in a stagnant water column, Figure 5.7a. This result implies that the flow around the bubble in the water film nearly matches the upward displacement of water by the rising bubble. On the other hand, when the shaft diameter is much smaller, the bubble as well as the water surface interface rise at rates about an order of magnitude greater than the Taylor bubble result, Figure 5.7b. Nearly all the experiments with the two smallest diameter shafts rose to the top of the vertical riser shaft, some explosively; while almost all experiments with the two largest diameter shafts exhibited conditions where the water was contained within the shaft.

Surges at Tail End of Air Pocket

The experiments in the second experimental configuration showed a wide variation of behavior. In the case where the horizontal pipe was initially 50% or 70% full, a more conventional hydraulic bore formed, generally with a large amount of air entrained into it. In contrast, the 95% full pipe was observed to pressurize almost immediately and often air in discrete pockets was trapped behind the pressurization front.

(a.) 57 mm Diameter Tower

(b.) 12.7 mm Diameter Tower

Figure 5.7 Representative bubble rise velocities for the smallest shaft diameter.

It is not totally clear where this trapped air originated from since the experimental protocol attempted to purge all air in the line upstream of the butterfly valve. However, the opening of the butterfly valve introduces some irregularities into the flow, probably resulting in surface waves that travel rapidly after closing the pipe section. Since the discrete air pockets formed upstream from the riser, they entered the riser and at least in the smallest diameter shaft behaved similarly to a Taylor bubble. Because the surge shaft was close to 2 m in height and water in some cases rose a considerable height up the riser, the video camera had to be maintained at a large distance so that it was difficult to obtain accurate measurements of water surface elevations from the video images. Most of the following results are from the pressure measurements from the transducer mounted near the bottom of the riser.

The pressure histories varied considerably between the fully vented and the non-vented riser conditions. In general, the fully vented risers exhibited longer inertial oscillations, see Figure 5.8 that appeared to be associated with oscillations in the flow in the horizontal pipeline. In contrast, when the riser was closed at the top to prevent air escape, the water surface variations in the riser were much less but the pressure variations are comparable to the vented case except that the pressure fluctuations are associated with the compression of the trapped air within the riser, see Figure 5.9. The pressure oscillations were of much higher frequency and were most likely associated with pressure oscillations associated with the compression of the air.

Interestingly, the diameter of the riser has very little effect on the magnitude of the maximum pressure surge measured, nor was the degree of venting at the top of the riser very important. Figure 5.10 depicts the results that lead to these conclusions. When the surge is measured in terms of the pressure at the bottom of the riser, the non-vented risers result in slightly higher pressures; this is probably due to the smaller motion within the riser resulting in lower energy losses at the riser entrance. Raising the upstream reservoir elevation increases the magnitude of the pressure surges as indicated in Figure 5.11. The interpretation of these results is that the magnitude of the surge in these experiments is primarily controlled by the pressure level on the back side of the pressurization bore which in turn is dependent on the two primary variables of initial water depths in the horizontal pipe and reservoir head. The riser shaft appears to only provide a mechanism for this pressure head to be converted into a riser surge and the details of the riser do not appear to be very important.

Figure 5.8 Typical pressure plot with open ventilation at top of vertical shaft.

Figure 5.9 Typical pressure plot with closed ventilation at top of vertical shaft.

Figure 5.10 Effect of ventilation and riser diameter on peak surge pressure (reservoir elevation = 0.703 m, initial water depth = 50% full).

Figure 5.11 Effect of reservoir elevation on peak surge pressure (riser diameter = 12.7 mm).

An attempt was made to assess the potential significance of the density of the air-water mixture at the bore front on the magnitude of the surge that was generated in the vertical riser. In order to perform this assessment, the maximum pressure head measured with the pressure transducer at the

bottom of the riser was compared to the maximum water surface elevation observed within the shaft during the surge event. This comparison was only performed for the two largest shaft diameters as the water surface was more difficult to interpret from the video images for the small diameter shaft. In addition, the comparison is only made for the two smallest initial water depths within the horizontal pipes. Figure 5.12 presents the results of this comparison. The results of the two measures of surge are basically the same. Since the reduced density of an air-water mixture would require a greater height to produce the same pressure level as a solid water column, it is concluded that the air bubbles entrained at the pipe-filling bore do not play a significant role on the ensuing surge.

Figure 5.12 Comparison of peak pressure surge measured with pressure transducer and that scaled from videos.

5.4.2 Effects of Experimental Model Scale

Experimental observations made in these investigations differed in some significant ways from the image presented in Figure 5.1. Probably the most significant is that Figure 5.1 clearly indicates a mixture of air and water erupting through the manhole.

In contrast, videos from the preliminary experiments with very large surge heights seem to indicate that the fluid is almost exclusively water. This raises some potentially important questions such as whether the

air-water mixture in Figure 5.1 was generated in the horizontal flow within the pipeline (e.g. due to the entrainment of air at inflow dropshafts) or whether conclusions from these investigations can be generalized to full-scale sewers, even qualitatively. The first issue also calls into question previous research that has been conducted on the problem of rapid filling in near horizontal pipelines (e.g. Vasconcelos and Wright, 2005) if air entrained at inflow points migrates as a bubbly mixture and subsequently is released through a geyser. The horizontal flow in those previous experiments was basically a stratified two-phase flow with very little dispersed air in the flow. Although the potential significance of air entrainment at inflow points is not discounted, it seems likely that buoyancy effects would tend to concentrate air at the top of the pipeline after relatively short travel distances for conditions that would be typical of large stormwater tunnels. However, it would be useful to have measurements in prototype tunnels to understand the origin of air that is vented through the geysering phenomenon.

Two-phase flow in conduits is a complex process. Horizontal flow is generally described by a classification system that describes the interaction between the two phases (e.g. Weisman, et al., 1979). The flow may be described as stratified, wavy, slug, annular or dispersed with wavy or stratified corresponding to flow systems with the water at the bottom of the conduit and air at the top and dispersed flow involves smaller air bubbles mixed more or less uniformly through the flow. Similar sorts of classifications would be associated with two-phase flow in vertical conduits, Taitel, et al., 1980. The formation of a Taylor bubble falls into the slug flow classification system. The film flow around the perimeter of the Taylor bubble can exist in either a laminar or turbulent state, depending on the magnitude of a suitable Reynolds number. Regardless of this state, a type of interfacial instability referred to as flooding can develop if the velocity difference between the air-phase and the film flow is sufficiently large. These instabilities can grow and eventually water droplets are sheared off the film and entrained into the rising bubble. This is the mechanism that is visualized as responsible for the formation of the geyser in Figure 5.1. Criteria for predicting the onset of the flooding instability are not well understood, but Guedes de Carvalho, et al. (2000) report that the relative velocity required for the onset of flooding instability for air at atmospheric pressure is 7.4 m/s for a 19.2 mm diameter tube and 2.8 m/s for a 32.8 mm tube. The required velocity decreases with increasing gas density due to pressurization of the air, for example. Although we have no direct measurements of the film velocity, the velocity of the rising air bubble never

exceeded 1.7 m/s in the 12.7 mm diameter tube or 0.35 m/s in the 44.4 mm diameter tube. Thus, it appears that with the experimental conditions implemented, the two-phase flow was not even close to the flooding instability. In contrast, if the rise of the geyser is converted into a velocity head, it appears that the exit velocity of the flow in Figure 5.1 was on the order of 15-20 m/s and well above the transition limit that would be suggested in the literature although it is stressed that the transition to flooding instability is not well understood.

There are a number of aspects to the various experiments that will not scale directly to a prototype scale. In the case of the surging associated with the head of a trapped air pocket, there is the flooding instability described above. At the laboratory scale, the film flow is almost certainly in a laminar state, whereas it would be turbulent at larger scales. Another aspect that would not be reproduced correctly is the compression of the entrapped air. At the laboratory scale with riser heights on the order of 0.5 m or less, air would basically behave as an incompressible fluid. In contrast, in a deep storage tunnel, water could be standing in a riser to a depth of the order of 10 m prior to the arrival of the air; this would result in an expansion of the air as it rose vertically in the shaft, exacerbating the surge process. In the case of surging initiated by the tail of the air pocket, presumably the size and number of air bubbles entrained into the bore propagating in the horizontal pipeline would not scale properly. However, the results presented above suggest that this air has little impact on the surging process.

These considerations indicate that the magnitude of the surges observed, especially those associated with the displacement of water standing in a pressurized riser would not scale properly from the laboratory to prototype conditions. However, the mechanisms driving the surges have apparently been reproduced consistently. It remains to be demonstrated by adequate measurements in prototype systems whether these mechanisms are critical to observed geysering phenomena or whether analyses based on these processes could provide a basis for design to avoid these events.

5.5 Conclusions

The experiments presented in this investigation are believed to be the first involved with an examination of surges in vertical risers attached to a pipeline that is undergoing a flow regime transition. Results from previous studies (e.g. Vasconcelos and Wright, 2003) did not indicate significant

surges associated with the initial flow regime transition from free surface to pressurized flow, but that subsequent surges could occur upon the arrival of large entrapped air pockets at a small diameter riser located in the crown of a pipeline. Strong surges were noted in the riser both as the arriving air pocket resulted in a Taylor bubble displacing the water existing within the pressurized riser and as the water at the tail end of the air pocket arrives at a now evacuated riser. Simplified experiments were conducted to examine both of these events in more detail in which key variables could be systematically varied to establish their importance in determining the magnitude of observed surges. The following conclusions were derived from the results of these sets of experiments:

- The initial surge associated with the arrival of an air pocket at a riser partially filled with water is due to the rise of a Taylor bubble in the shaft. Although there is a film flow downwards around the perimeter of the Taylor bubble, the water is also displaced upwards as the film flow does not allow sufficient downward discharge to counteract the rising bubble;
- For sufficiently large shaft diameters, the film flow is nearly sufficient to prevent upward displacement of the water in the shaft but for small shaft diameters, the water is displaced explosively in the vertical direction as the film flow is apparently insufficient to allow the downward water flow to offset the rising air bubble;
- The only variable that was investigated that had a significant impact on the magnitude of the surges generated by rising Taylor bubbles was the shaft diameter. This suggests that the magnitude of ventilation shaft diameters may be a critical issue in geyser formation.
- With respect to the surges initiated by the arrival of the pressurized water at the back of the air pocket, the characteristics of the surge riser such as shaft diameter do not have a significant impact on the surge behavior;
- The magnitude of the pressure behind the air pocket which depends on the strength of the pipe filling process appears to be the key variable controlling the magnitude of the surge;
- The magnitude of the surge does not appear to be connected to the presence of a bubbly air-water mixture at the tail of the air pocket implying that numerical models

that consider the air and water as distinct phases should be able to predict the surge magnitudes;

- Given the above conclusions, it appears that strong geysering events are most likely associated with the arrival of a large pocket of trapped air at a vertical shaft. Although the experiments performed showed no vertical air-water jets such as has been observed in prototype systems, this is most likely due to the fact that the flow conditions in the laboratory experiments are below the threshold for flooding instability in which water droplets will be sheared off the film flow interface and carried upwards in the Taylor bubble. A sufficiently large scale experimental apparatus may be able to capture this phenomenon, but would not be possible to create at the scale of the current experiments.

The results of these experiments have shed some light on the likely mechanisms for the geysering process. Additional confirmation at a field scale would be desirable to back up these tentative conclusions. Perhaps the most significant observation is that ventilation shafts can be susceptible to geysering if the shaft diameter is too small. It is not obvious that the results from the present study can be scaled up to provide design recommendations due to the presence of several scale effects that do not properly account for prototype behavior. Additional consideration of possible geometry alterations to minimize the effect of a Taylor bubble could be a productive area for additional research.

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