MODELING RAPID FILLING PROCESSES IN STORMWATER TUNNEL SYSTEMS

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ABSTRACT

The deep tunnel and reservoir project (TARP) in Chicago and several other combined sewer or stormwater systems have intermittently experienced events typically referred to as geysers which involve eruptions of water or water/air mixtures from vertical access or ventilation shafts that often spray tens of meters into the air. Geyser events can lead to public health or safety impacts. A fair amount of research has been conducted to understand the phenomenon and to develop methods for controlling or eliminating such occurrences. The literature on the subject is somewhat confusing due to an apparent lack of understanding of the circumstances that can lead to geyser formation. Much of the early work proceeded from an analysis of single phase flow (water) modeling under the premise that inertial surges in rapidly filling conduits were the essential mechanisms for geyser formation and the role of air in the process was neglected. Although this assumption leads to simpler model formulations, evidence from videos often fortuitously recording geyser events and limited quantitative data suggests that the assumption is often insufficient to account for observations. A brief review of some available data to support this contention will be presented. Results are also presented from controlled laboratory experiments involving the release of an entrapped pocket of air through a vertical shaft that can be interpreted as geysers. These experiments were carefully performed to eliminate inertial surges as a cause for the observed conditions. These results lead to the conclusion that a significant cause of geyser formation in at least some situations is the release of a trapped volume of air through a vertical shaft. This led to the formulation of a numerical modeling scheme that is capable of resolving the sharp filling fronts that can develop in a rapidly filling stormwater system. A discussion of model limitations and modifications that are being explored to more faithfully represent trapped air interactions is provided.

1. INTRODUCTION

Storage tunnels have become an accepted solution for managing inflows into combined sewer systems to reduce pollution to surface water bodies by reducing the frequency and volume of overflows while also preventing system backups. One of the earliest implementations of a storage tunnel system is in Chicago, Illinois which is referred to as the TARP (Tunnel and Reservoir Plan). This project consists of over 170 km of 3-10 m diameter tunnels that were constructed up to 107 m below grade. Events that have subsequently been referred to as “geysers” were experienced soon after implementation of the initial phases of the project. A geyser involved the displacement of manhole covers from tunnel access shafts and an eruption of sewage up to tens of meters vertically. Similar observations have been made in a number of other stormwater and combined sewer systems. Figure 1 shows images from videos that have been made in different systems, many of which appear on YouTube [https://www.youtube.com]. Some videos appear to indicate a composition primarily of water with only minimal vertical rise; some are primarily air, while the majority with large rise heights appear to be a mixture of water and air. Since becoming involved in this research, correspondence with other engineers has drawn attention to generally similar phenomena in a hydroelectric tunnel system [1] and in a karst aquifer recharge system in Florida [personal communication]. In both of these related systems, entrained air appears to be a key part of the behavior.

a.) b.)

Figure 1: Images from videotapes of geysers in sewer systems in a.) Minneapolis, Minnesota and b.) Chicago Illinois.

Early investigations dealing with geysers attributed the phenomenon to inertial surges in a rapidly filling tunnel requiring only a single phase flow model formulation [2,3]. For example, a statement in the literature is that "…if the water level rises above the ground surface, the geyser occurs. It has been ascertained that if the dropshaft is ventilated, as most are, the cover could not be blown off by air pressure alone. That is, most blowoffs are caused by the impact forces of the rising water. Therefore it is sufficient to study the hydrodynamics alone." [4]. At best, these statements are only precise for manholes with large ventilation openings and may not be sufficiently general to describe the phenomena depicted in Figure 1 since some filling processes could involve the displacement of large air volumes.

An important issue is whether the presence of air is an essential part of geyser formation and therefore must be considered in analyses of rapidly filling stormwater systems in order to anticipate the likelihood for the formation of geysers. This manuscript summarizes the results of a number of studies that address this issue as well as modeling approaches for assessing operational difficulties in storage tunnels and other stormwater systems.

2. GEYSER MECHANISMS

The author was involved in a preliminary study to investigate rapid filling of a nearly horizontal conduit and observed that entrapment of relatively large pockets of air was commonplace [5,6]. It was also observed that vertical eruptions of air plus water could occur through vertical risers connected to the top of the conduit as the air pocket arrived at the riser. Under these circumstances, the conduit was pressurized such that water was standing at some level within the vertical shaft prior to the arrival of the air pocket. As the air pocket arrived at the surcharged riser, it began to rise due to its buoyancy, forcing the water upwards ahead of it but with a downward flow around the circumference of the riser similar to air intrusion at the bottom of a water filled vertical tube [7]. At the small scale, the fluid behaviour did not resemble the behaviour observed in the much larger geysers depicted in Figure 1, but it seemed plausible that the essential mechanism responsible for geyser formation was being reproduced. It is noted that while inertial surge may have been occurring in some laboratory experiments, depending on the flow condition established, surge was not a required component of the experiment in order to produce strong vertical ejections through the riser but air was always involved with strong releases.

2.1. Field Observations

Pressure measurements and video records were collected within a stormwater tunnel in Minneapolis, Minnesota that regularly experienced geysers. Measurements were made at a manhole where geysers were frequently observed. Figure 2 is a pressure record following a storm event that resulted in a series of discrete geyser events separated by about one minute intervals. Since the tunnel invert is 28.6 m below grade and the pressure heads are represented relative to the tunnel invert, it was concluded that inertial surge was not a significant influence during these events and that pressure heads would be insufficient to raise the water in the manhole shaft to levels even approaching the ground surface [8,9] while the observed geyser was on the order of 20 m above the ground surface. This led to the conclusion that the geysers must be a complex interaction of a mixture of air and water and that failure to consider the role of air in geyser formation in at least some systems would be insufficient to describe the process. The conclusion was that while inertial surge may be responsible for geyser formation under certain circumstances, it is unlikely to be a sufficient mechanism to create observed geysers in most circumstances.

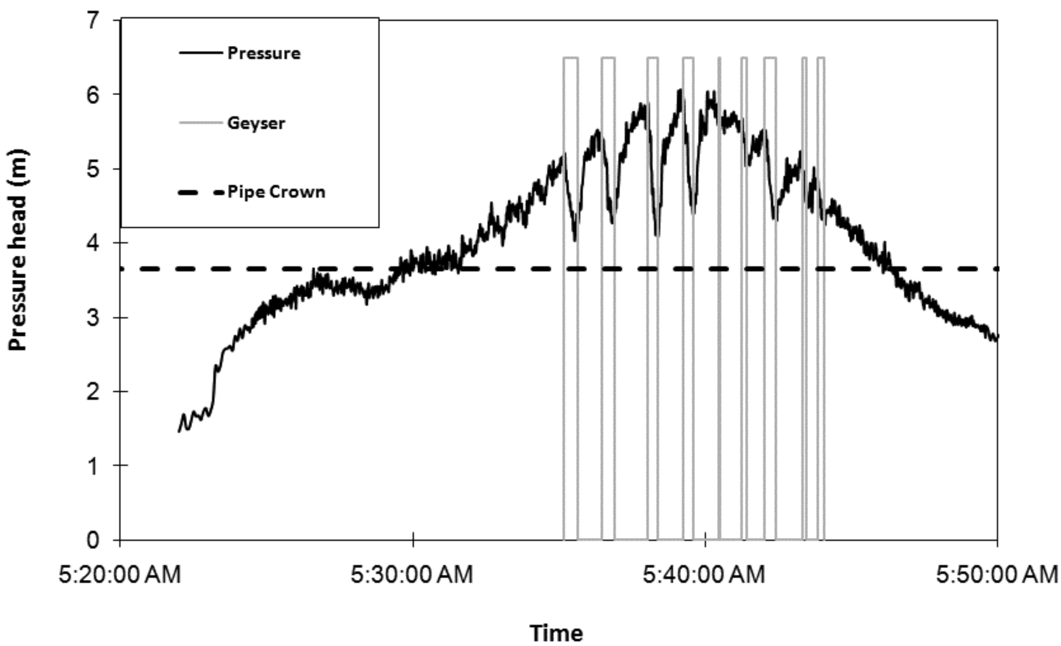


Figure 2: Title of pressure measurement during geyser episode in Minneapolis, Minnesota stormwater system. Gray lines depict the times during which geysers are visible on videotape (no scale). Dashed line depicts pipe crown, flow is surcharged when pressure is above pipe crown.

2.2. Laboratory Observations

A set of carefully designed laboratory experiments were performed to demonstrate that inertial surge was not a necessary requirement for geyser formation. These involved the experimental setup indicated schematically in Figure 3. A discrete pocket of air was isolated behind a quick opening valve at one end of a pipeline that was otherwise filled with stagnant water maintained at a constant pressure by the presence of a constant head reservoir at the opposite end of the pipeline. The air pocket was maintained at a pressure to match the reservoir head. A vertical riser was installed in the pipeline at a location relatively close to the reservoir end and the riser diameter was a key control variable in the experiments along with the air volume. When the isolation valve was suddenly opened, an air intrusion into the water filled portion of the pipe creating a situation such as analysed by Benjamin [10]. As the air intrusion reached the riser, an event considered to be geyser formation at the small laboratory scale was observed. A pressure trace measured near the bottom of the vertical riser and presented in Figure 4 for a typical experiment closely resembles the pressure response observed in Figure 2. Figure 4 also presents an expansion of the pressure record presented in Figure 2 so that more detail can be observed in the Minneapolis stormwater system, again suggesting that the essential mechanism for geyser formation in at least some stormwater systems was reproduced. In cases where the riser diameter was much smaller than the horizontal pipe diameter, the rising air is capable of lifting water distances significantly greater than the reservoir head as depicted in Figure 5. Results presented in this figure include what is referred to as breakthrough (BT) in which the rising air pocket in the vertical riser reaches the rising water surface in the riser while the term splash indicates the maximum rise height of the water which is lifted further by the rising air, i.e. the laboratory version of the geyser. These results suggest that geysers can be significantly controlled by designing sewer systems with vertical shafts on the order of the conduit diameter or larger and this guidance has already been incorporated into the design of stormwater tunnel systems in Washington DC USA and London UK.

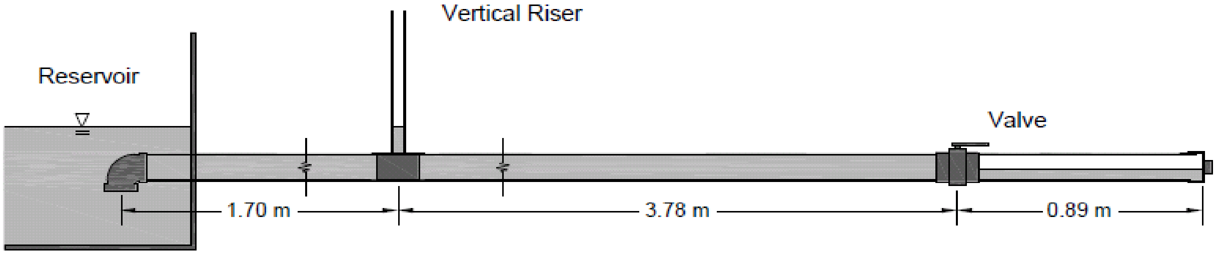
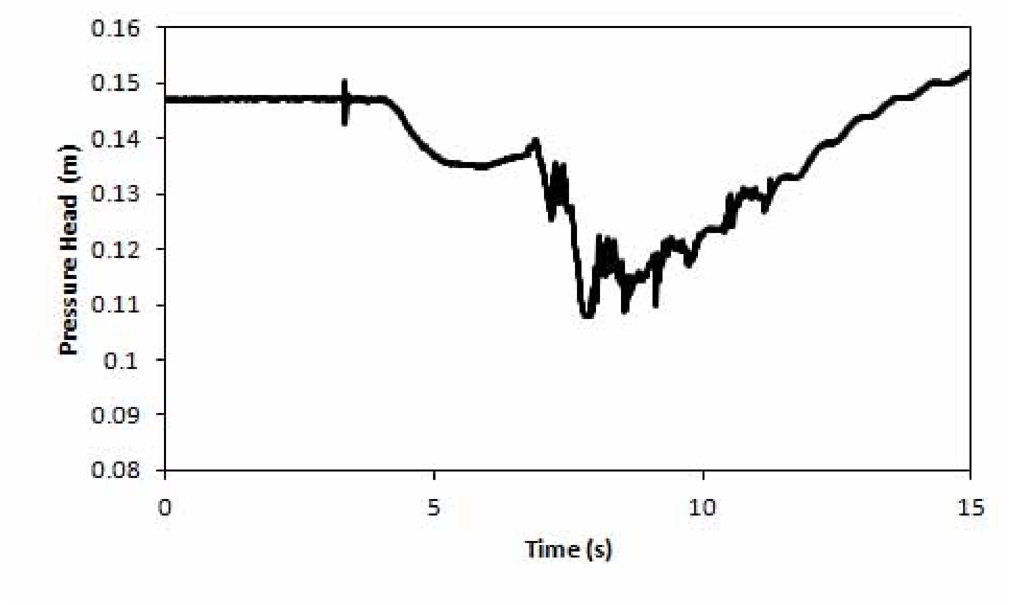
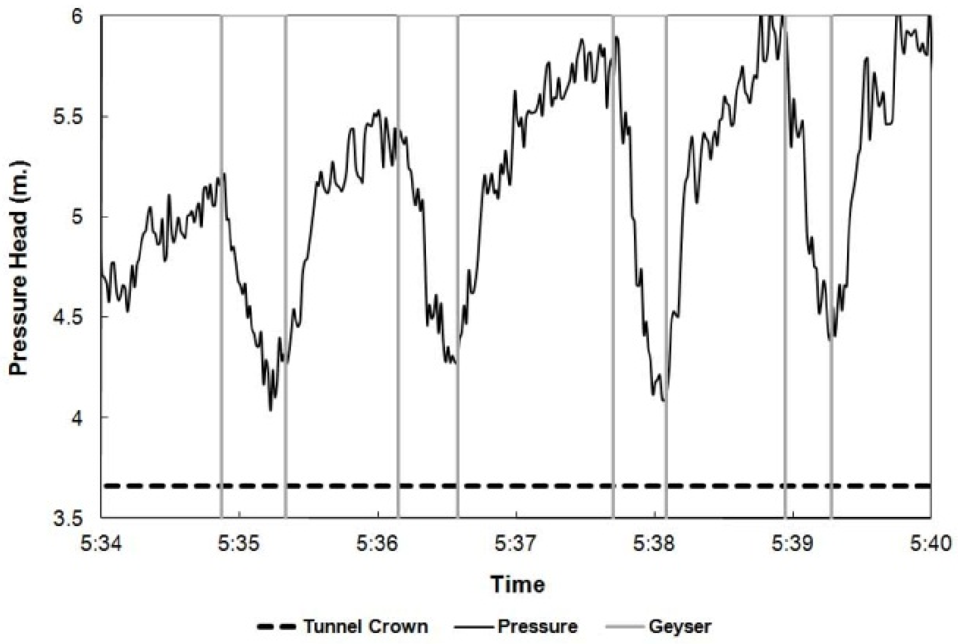


Figure 3: Schematic of experimental apparatus to observe water displacement in vertical riser by air pocket.



a.)



b.)

Figure 4. Pressure measurements a.) single geyser in laboratory experiment, and b.) multiple geysers as indicated in Figure 2.

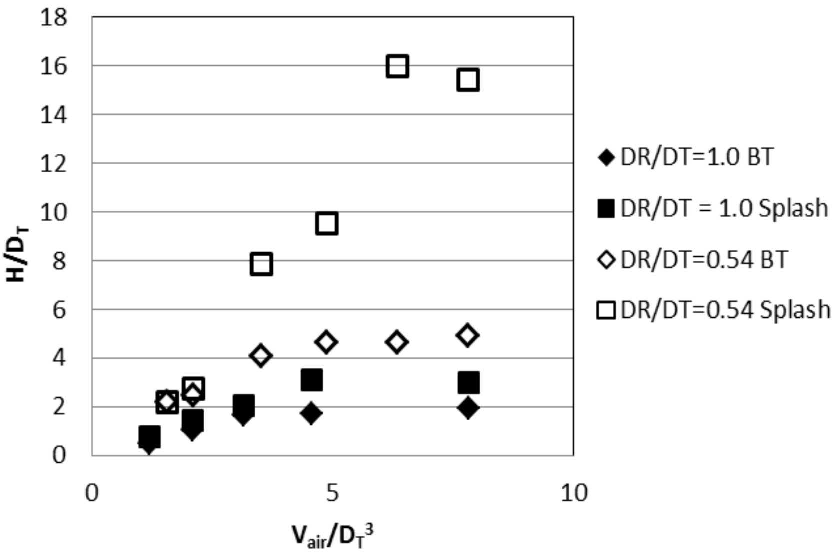


Figure 5. Rise heights for two different riser diameters (riser diameter/tunnel diameter of 0.54 and 1.0)

3. NUMERICAL MODELING

3.1. Modeling Approaches

Most numerical models to describe rapidly filling stormwater systems that have been developed in recent years have been of the single phase flow type [11-14]. This decision is generally controlled by the computational requirements for describing a flow that may simultaneously exhibit free surface and pressurized flow in different parts of a sewer system and the large lengths that are associated with typical systems, making the application of a three-dimensional multi-phase flow model infeasible. At the least, a single phase flow model must be capable of accurately resolving transitions between free surface and pressurized flow and two general types of models have been formulated for this purpose. Earlier models as well as some more recent ones are of the shock fitting type [11-13]. This approach develops a separate set of equations for free surface (St. Venant equations) and for pressurized flow and applies the appropriate set at any location depending on the local flow state. In many instances the transition between free surface and pressurized flow occurs as a hydraulic bore and it becomes necessary to keep track of the location of the bore front that is presumed to provide the transition between free surface and pressurized flow. This is accomplished by writing local conservation equations for mass and momentum in the frame of reference of the bore, solving for the bore speed, and keeping track of the propagation of the bore front with time. This is necessarily a complex process in an actual tunnel system where spur tunnels and geometry transitions may result in multiple bore fronts that may interact with each other. Some models resort to unrealistic simplifying assumptions such as that when a ppipe-filling bore forms, it can never evolve into a normal free surface bore with free surface flow on either side [11]. Laboratory studies show that either type of bore can exist in filling conduits [15].

An alternative numerical scheme referred to as a shock capturing scheme was developed by Cunge [16] and others and uses a numerical artifact to handle the flow regime transition between free surface and pressurized flow. Cunge implemented what he called a Preissman slot which is an imaginary slot located at the top of the circular conduit. Since the speed of an elementary wave in free surface flow is given by $c = (A/T)^{1/2}$ with c the wave phase speed, A the cross-sectional area and T the channel top width, selection of the slot width can result in a desired value of the pressurized flow (water surface within the slot) celerity that could describe the acoustic wave speed of a pressurized flow. In the original work by Cunge, an implicit numerical scheme was implemented and the slot width was chosen to provide computationally convenient simulation conditions. A very small slot width could be selected so as to provide an appropriate acoustic wave speed for water flow systems [17] although it is clearly an open question what the appropriate wave speed should be in a typical stormwater system that may contain a significant amount of entrained air. In a modification to the Preissman slot concept, a similar approach was taken [14,18] that used a hypothetical pipe wall elasticity to provide the mechanism for simulating acoustic wave phenomena in pressurized flows. This method has been referred to as the two-component pressure approach or TPA. The governing mass and momentum conservation equations for free surface flow (St. Venant equations) are given as

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A} + gA(h_c + h_s)\right) = gA(S_o - S_f) \qquad (2)$$

In which A is the flow cross-sectional area, Q is the discharge, g is gravitational acceleration, h_c is the pressure at the centroid of the flow area, h_s is surcharge pressure for pressurized flow, S_o is bottom slope and S_f is friction slope. If the flow has a free surface and is not surcharged, then $h_s = 0$ and the equation applies for conventional free surface flow. The pressure term h_c can be written as $c^2(2Q/A)$ for free surface flow with c the wave celerity as given above. For pressurized flow, A is the full conduit area A_p and $h_s = (a^2/g)(\Delta A/A_p)$ with a the acoustic wave speed for a rigid conduit and ΔA is the change in A_p due to elasticity under a change in pressure. Therefore, Equation 2 can be applied for either free surface flow or surcharged flow with the appropriate wave speed for each case. A term by term comparison of the St. Venant and waterhammer equations for a rigid pipe shows that the two sets of equations are equivalent so long as the appropriate phase speed and pressure terms are used for free surface or pressurized flow depending on the local flow state. This method is implemented with a finite volume method implementing Roe's first order upwind scheme [14] and has proven quite robust in applications to modeling proposed stormwater storage tunnel systems [19]. Full details of the implementation scheme are provided in [14]. It is necessary however, to be able to distinguish whether or not sub-atmospheric pressures or free surface flow will occur at some locations within a system. This will depend on whether there is a source for air to enter through a ventilation shaft or other source at the location where a pressure decrease is being predicted that could result in the re-establishment of free surface flow. The numerical model must be informed as to whether a source of ventilation is present at any computational node.

3.2. Modeling issues

Since the TPA model is capable of simulating waterhammer conditions [18] the choice of an acoustic wave speed to correctly represent a rigid conduit with no entrained air will necessitate very small time steps in order to satisfy the Courant condition with the explicit numerical scheme. This may make applications to large tunnel systems computationally extremely challenging; the same problem is encountered with the Preissman slot scheme if an explicit numerical procedure is implemented. A traditional approach in that case is to use a larger slot width to effectively reduce the acoustic wave speed, resulting in larger and computationally more feasible numerical time steps. This is often justified for stormwater applications where it is argued that waterhammer effects are not generally present and it is only necessary to describe the inertial surge in the system. In the TPA model, the same approach is implemented by essentially assuming a very elastic conduit wall which also lowers the simulation acoustic wave speed, resulting in larger computational time steps. In principle it is possible to argue that the acoustic wave speed is smaller due to entrained air [17] but the effect is numerically accounted for by employing the elastic pipe wall concept. It is noted, however, that both the TPA and Preissman with inappropriate system description do not really satisfy a true conservation of mass, a result of the computational artifacts of the formulations. So the acoustic wave speed cannot be arbitrarily lowered and still obtain accurate computational results. It has been found in applications that an acoustic wave speed on the order of 200-300 m/s does not excessively alter the mass balance and provides significant computational efficiencies

Although the TPA model described does not include the effects of air in the system response, it is actually capable of predicting where air entrapment would occur, at least in some instances and is capable of providing estimates of the trapped air volume. Experience gained in modeling of the Thames Tideway Tunnel system in the London UK area are discussed to demonstrate the principles involved. Two scenarios have been simulated that result in the predicted entrapment of air. This system is typical of many storage tunnel systems that are filled at multiple inflow points into a deep tunnel that has a small downward slope essentially towards a dead end. As the tunnel goes full, a hydraulic bore will develop at this end and begin to propagate towards the opposite end of the tunnel. Although the bore is initially of the pipe-filling type, it loses strength during the upstream propagation due to the combined effect of friction and the local storage in spur tunnels and/or vertical shafts. A free surface bore may be predicted to develop at some location with a transition to a full conduit condition through a gradually sloping interface behind the bore. If this bore arrives at a tunnel transition (In the Thames Tideway Tunnel application, it is a vertical drop in the tunnel grade but other geometrical transitions are possible), the resulting reflection generates a pipe-filling bore that propagates towards the filling transition, resulting in the entrapment of a long thin volume of air above the original sloping interface. A second condition that results in air entrapment is the arrival of a pipe-filling bore at a vertical shaft or spur tunnel (these often occur in combination). The storage results in the inability to maintain the pipe-filling condition and an air intrusion would develop propagating towards the downstream filled end of the tunnel. The filling of the storage element, however, eventually raises the water level at the shaft above the tunnel crown and an air pocket is trapped.

Since the model formulation does not actually model the presence of air, it is computationally treated as a void. This void will subsequently vanish as a natural consequence of the simulation and a waterhammer wave will be predicted following the void collapse with subsequent pressure oscillations throughout the system, including the possibility of subatmospheric pressures being predicted which could potentially damage the tunnel lining if they were real. However, these waterhammer pressures are not physical since the void predicted is actually occupied by air that would be compressed as that volume is reduced. It is known however, that compression of trapped air inside a system can also result in pressure increases and subsequent pressure oscillations [20]. In contrast to the waterhammer predictions, small entrapped air volumes result in larger pressure fluctuations as opposed to smaller ones predicted by waterhammer theory associated with the collapse of small voids. Therefore, the model predictions with the TPA model are not realistic but should not necessarily be considered to be conservative in nature since the numerical treatment is incompatible with the true physics. In particular, the pressure rise in the computational scheme depends on the chosen acoustic wave speed in accordance with waterhammer theory while the air compression converts the problem to an inertial surge that is independent of wave speed.

Some preliminary experiments were performed in order to understand the nature of pressure fluctuations due to compression of an entrapped pocket of air by an advancing hydraulic bore [21]. These experiments were somewhat artificial in order to provide a straightforward experiment and involved an isolation valve at the entrance of a pipeline connected to a constant head reservoir, this valve was normally closed. At a location towards the opposite end of the pipeline, a ventilation riser with a second normally open valve located at its base, see Figure 6. Upon the sudden opening of the first valve into the partially filled pipe, a pipe-filling bore propagated pushing the air ahead of it. As the bore advances down the pipeline, the second valve was suddenly closed, trapping a volume of air ahead of the advancing bore. The subsequent pressure variation within the trapped air was measured and Figure 7 presents a typical result. The generalized results are presented in Figure 8 with

$$P^*_{max} = \frac{P_{max}}{\rho g D \dfrac{A^2}{(A_0(A - A_0))}} \quad (3)$$

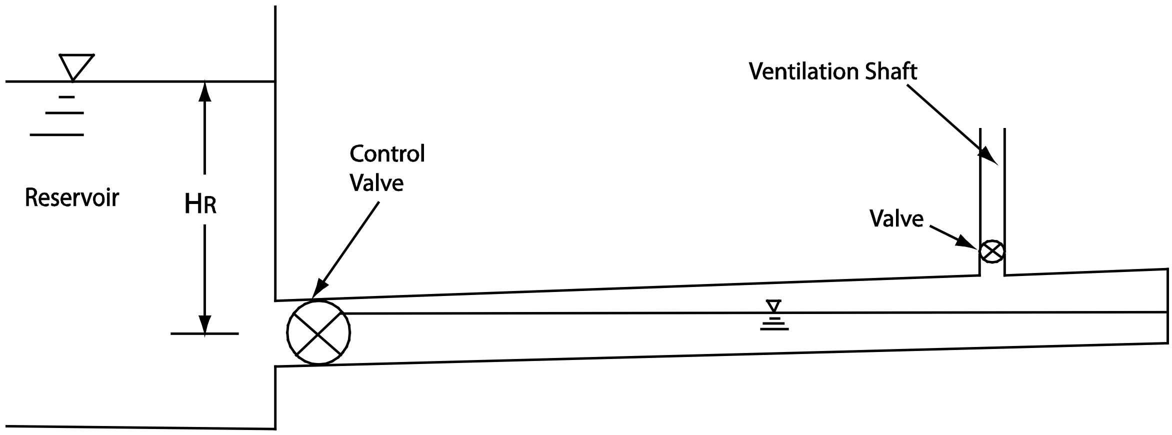


Figure 6: Schematic of experimental apparatus to measure pressure transients due to air compression against an advancing hydraulic bore.

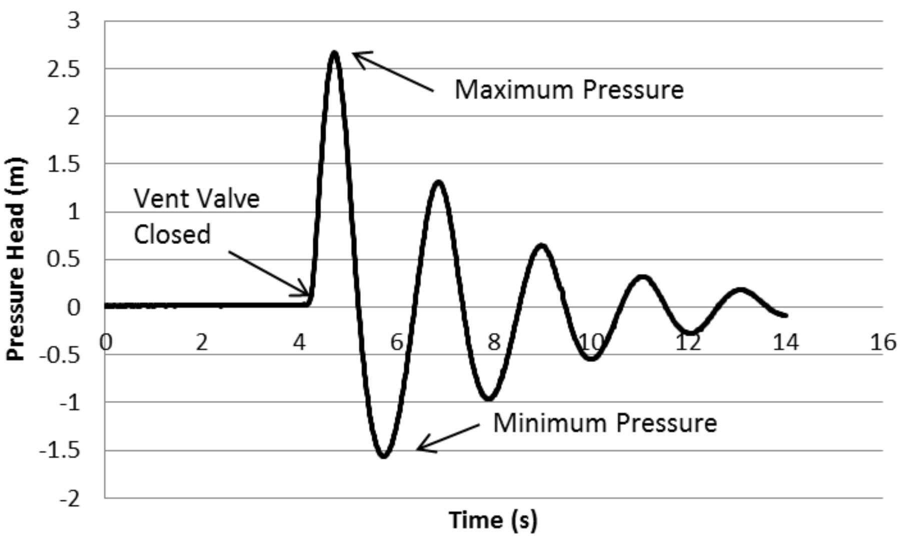


Figure 7: Typical pressure transient.

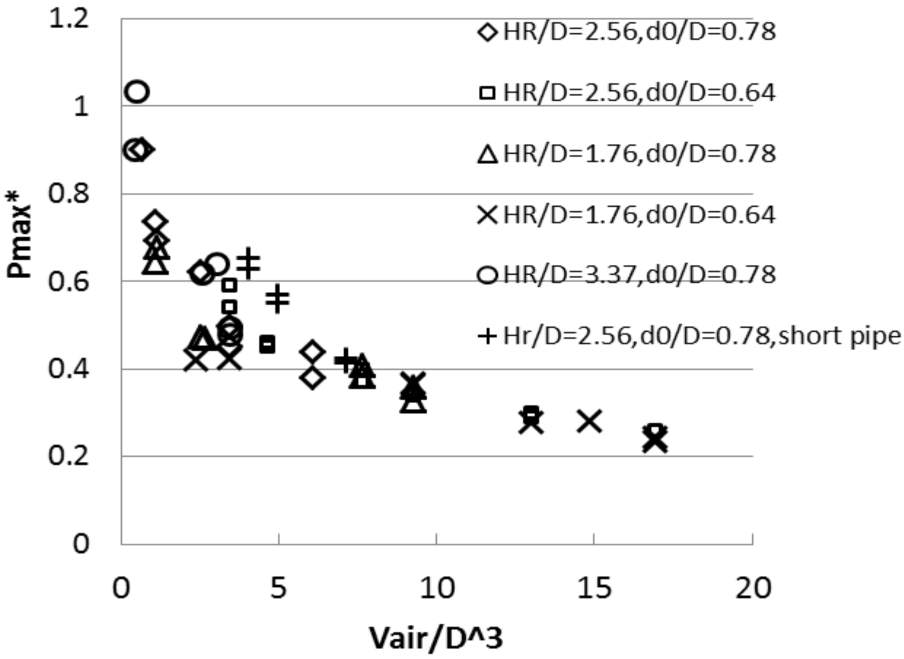


Figure 8: Measured maximum pressures for various experimental configurations and air volumes.

in which the form of the dimensionless maximum pressure P^*_{max} was derived by an approximation to the momentum equation requiring an excess air pressure to equal the momentum in the advancing hydraulic bore. Here *D* is the pipe diameter, *A* is the cross-sectional area of the pipe and A_0 is the area occupied by water ahead of the advancing bore. These results confirm that smaller trapped air volumes do in fact result in larger pressure rises as expected by the general results in simpler systems [20]. Note that of the two scenarios associated with air entrapment, the first involves the arresting of an advancing bore, but with relatively large trapped air volumes in most cases while the second case actually involves an air intrusion where the system inertia is quite small even though the air volumes may be much smaller. Therefore, it appears that concerns about large positive or sub-atmospheric pressures are not too important with the geometry of the proposed Thames Tideway Tunnel system. A modified version of the TPA model that incorporates the volume of air predicted to be trapped by the conventional framework as a fixed mass of air that cannot move any substantial distance during the short duration pressure transient and therefore is constrained to remain at the location when the air pocket formed. Equations that computed the changes in air volume due to pressure variations have been implemented and the resulting solution appear to substantiate the conclusion that pressure increases due to air compression are modest. It should be noted that no experimental verification of this conclusion has been presented to date but plans are underway for accomplishing this objective. It should also be stated that this conclusion may not be general due to complexity of geometry in actual tunnel systems and careful consideration of the compression of trapped air is warranted at least until a sufficient understanding of the implications of this process are more fully understood.

4. CONCLUSIONS

This research was initiated by observations of a relatively unknown and damaging phenomenon in newly constructed stormwater systems. Progress in understanding the exact processes underlying the problem was hampered by the sporadic nature of geyser occurrence and the lack of adequate instrumentation in operational systems. As a consequence, attention was paid to the development of computational tools that, while simpler to develop, apparently did not contain all of the relevant processes. In the performance of some preliminary laboratory studies to more clearly define the focus of further research, it was observed that trapping of discrete large pockets of air could be relatively ubiquitous in the rapid filling of stormwater systems and that the subsequent release of that air through vertical ventilation shafts may be the source of the geyser phenomenon. Fortunately, access was provided to measurements in a stormwater system that was prone to geysering and the data unambiguously indicated that air must play an important role in that system. Parallel development of a numerical model to simulate the rapid filling process deepened additional insights as to mechanisms for air entrapment in prototype systems and also indicated issues associated with pressure transients in systems with entrapped air. Pursuing each question as it arose with some combination of laboratory and numerical investigations has provided insights as to how to resolve some of the issues related to the design of stormwater systems. It is expected that further insights will be generated by pursuing the new questions that always seem to arise with the advancement of research efforts.

It is concluded that the formation of what are generally referred to as sewer geysers is associated with air that is trapped in rapidly filling stormwater sewer systems. It is noted, however, that the literature is quite vague in many instances about how exactly a geyser is defined and the author unfortunately in some of early work contributed to this confusion by not being sufficiently precise in definitions of what was an unclear phenomenon at the time. It has also been seen that compression of trapped air pockets during a filling process may give rise to some potentially significant pressure transients. It remains to be established exactly what conditions are necessary to create significant pressures that may be the explanation for reported structural damage to stormwater systems [22,23] but with a clearer idea of the relevant processes, improvements in understanding and ultimately design recommendations can be anticipated.

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