GEYSERING IN RAPIDLY FILLING STORMWATER TUNNELS

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ABSTRACT

Events that are referred to as geysers have been observed in stormwater or combined sewer systems and are associated with jets of water rising through manholes to a considerable distance above the ground surface. Visual observations suggest that air may be a significant component of the jet. The mechanisms of geyser occurrence have been previously assumed to originate in inertial oscillations that force water up through vertical ventilation shafts. Recent laboratory investigations indicate that geyser formation is associated with the release of trapped air pockets through partially filled vertical shafts. Pressure data from a stormwater tunnel subject to infrequent geyser events is presented to indicate that measured piezometric heads adjacent to the ventilation shaft never increase to levels approaching the ground surface during a geyser event suggesting that air interactions must be an important part of the process. It is concluded that system design to avoid geyser formation must include the consideration of trapped air within the tunnel system.

CE Database Subject Headings: Combined sewers, stormwater management, underground storage, tunnels, surge, air-water interactions, buoyancy, geysering

INTRODUCTION

When stormwater or combined sewer overflow systems are filled rapidly, the phenomenon commonly referred to as "geysering" is of potential concern. Figure 1 is an image taken from a video recording of a geyser from a large diameter manhole in a stormwater collection system in Minneapolis, Minnesota. This particular image was from an event that occurred on July 13, 1997. Geysers have been observed in the operation of several combined sewer overflow storage tunnel projects and a design concern is how to avoid the occurrence. There appears to be some confusion in the literature about the origin of geysers, resulting in the possibility that the potential for geyser formation will not be properly accounted for in the design process and adequate measures for their mitigation will not be implemented.

A discussion of geysering was presented by Guo and Song (1991) and a photograph of a geyser is included in that paper. A similar discussion was presented in Guo (1989). However, the analyses presented in these papers describe the problem of inertial surge in vertical risers connected to a nearly horizontal pipeline. In order for this process to generate the event depicted in Figure 1, the piezometric head in the pipeline would need to extend well above ground level and water velocities in the manhole would need to be on the order of 20 m/s in order to provide rise height on the order of an estimated 20 m (assuming that the rise height is approximately equal to the velocity head in the manhole). The image

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appears to indicate a mixture of air and water, raising the possibility that interactions with air in the stormwater tunnel may be relevant to the geyser event. Geysers have also been reported in hydropower systems and were attributed to air entrained in a hydraulic jump within a portion of the piping system (Neilson and Davis, 2009). However, no instrumentation was installed in the system to document system behavior during the geyser occurrence.

The authors have been involved in extensive laboratory studies on transients associated with the rapid filling of nearly horizontal pipelines (e.g. Vasconcelos and Wright, 2005 and Wright et al., 2008). We have observed experimental events that we characterize as geyser formation. Observations suggest that geysers form as a result of the expulsion of large pockets of entrapped air through vertical ventilation shafts. Vasconcelos and Wright (2006) discuss a variety of flow processes that can result in air entrapment in rapidly filling pipelines while Vasconcelos (2005) presents the results of additional investigations on the interactions of trapped air pockets with surcharged vertical ventilation shafts. However, the jet exiting a vertical riser does not resemble that indicated in Figure 1, most likely due to scale effects in the much smaller laboratory experiment. While these experiments suggest the importance of air/water interactions, the limitations due to the relatively small scale laboratory experiments limit the ability to draw firm conclusions regarding field events.

Other studies have addressed the problem of air in pipelines, but the connection to the problem of geyser formation is unclear. Zhou, et al (2002) report on an experimental and numerical study of pressure rises due to compression of air in a rapidly filling pipeline with a restriction on the air escape. While this may be an important issue in the design of large sewers, it is not clear that there is any connection with geyser events. Li and McCorquodale (1999) discuss the motion of entrapped air pockets that are formed due to interfacial instabilities associated with the velocity shear at the air-water interface in the pipeline and present experimental data that show pressure spikes associated with air release through a vertical shaft. However, there is no discussion of geysers or any direct way to connect the small scale laboratory measurements to the event depicted in Figure 1. Wickenhäuser and Kriewitz (2009) report on experiments related to deaeration and release of entrained air in a hydropower tunnel; these bear some resemblance to some of the experiments mentioned above but do not directly address geyser formation. Izquierdo, et al (1999) report on the release of small air pockets from a filling pipeline such as a water main, where the air pocket is compressed and acts like a spring to increase the upward velocity of water in a riser.

A study was performed on the system shown in Figure 1 and pressure measurements were obtained during several geyser events. A record from one such event is presented below to suggest the importance of entrapped air in the geyser formation.

FIELD OBSERVATIONS

The video was recorded as part of a study commissioned by the Minnesota Department of Transportation due to the formation of geysers at the particular manhole in Figure 1 as well as a nearby one occurred that occurred following multiple large rainfall events. The study was conducted over about a ten

year period from 1996 to 2005. Modifications to the two manholes that experienced geyser formation were made in 2009 in an attempt to eliminate the phenomenon. The system is a 3.7 m high arch stormwater tunnel and the manhole is 2.4 m in diameter. The tunnel invert is 28.6 m below grade at the manhole location. Complete geometrical details of the tunnel were not provided, but it is understood that the manhole is located in a section of the tunnel with relatively flat slope with steeper slopes both upstream and downstream of the section with the manholes at which geysers were observed. A number of geyser occurrences (13 separate events between 1999 and 2005, for example) were recorded. In addition to the video records, two pressure transducers were installed in the tunnel as well as a velocity probe (Sigma velocity-area flow meter). The pressure transducers were located 0.47 and 2.88 m above the tunnel invert. Velocities and pressures were recorded at five minute intervals until the water level began to rise in the tunnel. Automatic controls on sample frequency resulted in the collection of pressure data once every five seconds if the water level in the tunnel was between 0.47 and 2.88 m and once per second for higher water levels. The particular data presented was collected on July 11, 2004 at approximately 5:30 AM. Nine independent geysers were observed in the video record of the event; although there is some variability, each geyser lasted for about 10-25 seconds with about 75-90 seconds separating the onset of each one. The velocity record indicates that the tunnel velocity was relatively constant at about 1 m/s between about 5:30 and 8:50 AM with no indication of fluctuations that would indicate inertial oscillations in the pipeline. The absence of inertial oscillations cannot be confirmed from the velocity records since velocity measurements are only made at five minute intervals.

The pressure history (lower pressure transducer) spanning the entire sequence of geysers is presented in Figure 2. The measured pressure is increased by 0.47 m so that the pressure head is relative to the tunnel invert. Superimposed on the pressure trace are the timing of the visual observations of individual geysers as well as the elevation of the tunnel crown. The tunnel is indicated to be in a surcharged state between about 5:29 and 5:46 spanning the duration of the geyser event (approximately 5:35 to 5:44). The maximum pressure head never rises above 6.0 m which is far below a value of 28.6 m that would be required to lift the water to grade under hydrostatic conditions. There is also no indication of inertial oscillations in the pressure record.

Figure 3 presents the lower probe measurements (both referenced to the tunnel invert) of about five minutes of the record during the middle of the geyser event. In general, the pressure is seen to follow a gradual rise associated with the rainfall event during this portion of the record as seen in Figure 2. The onset of an individual geyser is followed by a pressure drop that lasts until about the end of the geyser event after which the pressure tends to recover to the gradual trend.

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DISCUSSION

A qualitative explanation of how a geyser could occur due to the release of large air pockets is indicated in the conceptual sketch of Figure 4. A related discussion is presented in Wright, et al. (2007). A large air pocket reaches the vertical shaft and accelerates upward due to buoyancy effects. In some

respects, this resembles the phenomenon referred to as a Taylor bubble, that results as air intrudes into a vertical pipe capped at the top and initially filled with water (Davies and Taylor, 1950) However, the absence of a lid on the system results in the upward air flow transferring momentum to the liquid causing it to rise ahead of the air pocket with a downward leakage of water around the perimeter of the vertical pipe. This phenomenon was observed in the experiments reported in Vasconcelos (2005). However, since the volume of water in the surcharged manhole is apparently quite small according to the pressures indicated in Figure 2, it is expected that the water cap above the air is lost before the upward flow reaches the top of the manhole. Based on the rise height of the water jet (assumed to be roughly equal to the velocity head in the manhole, it appears that the rising air column will trigger the onset of flooding instability where the high velocity shear between the rising air and falling water generates interfacial instabilities as described, for example, by Guedes de Carvalho, et al. (1999). The large vertical air velocity then entrains water droplets and carries them upwards to form the observed geyser. This phenomenon was not observed in the small scale experiments by Vasconcelos (2005) since the velocity of the rising air bubble does not reach the magnitude suggested by Guedes de Carvalho, et al. to produce flooding instability and the air-water interface along the rising bubble remains smooth.

A remaining issue is the origin of the air that is responsible for the observed geysers. The limited measurements and the lack of detailed information prevent an absolute delineation of the source. However, the small surcharge in the flatter portion of the tunnel indicated in Figure 1 suggests that it is likely that free surface flow conditions existed in the steeper portions of the tunnel upstream and downstream from this section. Vasconcelos and Wright (2005) observed that air pockets could be transported in either direction once they are entrapped in a gently sloping pipeline, depending on the relative influence of gravity and hydrodynamic forces. Benjamin (1968) determined that the velocity required to prevent upstream migration of an air intrusion is $0.58\sqrt{(gD)}$ (where D is the pipe diameter) for horizontal, circular conduits. For the large diameter tunnel of this field investigation, the water velocity would need to be roughly 3.5 m/s in order to prevent upstream movement of an air pocket. Similarly the clearing velocity or velocity required to move air downstream has been shown to exceed $0.25\sqrt{(gD)}$ by Wickenhäuser and Kriewitz The required velocities for both these occurrences exceed the velocities of approximately 1 m/s measured in the tunnel. Therefore, the air pockets most likely originate by upstream intrusion of air from the steeper portion of the downstream tunnel.

One additional comment is that air compression does not seem to be an important part of these geyser events although it is possible to visualize that air expansion associated with decreasing pressures could enhance the geyser strength. Since the pressure heads are apparently never in excess of about 2 m according to Figure 2, very little air volume change would be expected in this system.

CONCLUSIONS

The field measurements are not as complete as might be desired but the above discussion appears to be consistent with the pressure measurements. The flow conditions within the tunnel are unknown except at

the measurement location and the events leading to the formation of possible air pockets are speculative. In spite of these uncertainties, the only plausible explanation for the geyser formation is the interaction of trapped air with water initially standing in the manhole shaft due to the existence of surcharge conditions. The measured pressures within the pipeline were incapable of lifting that water even close to the ground surface, let alone eject it 20 m or more into the air.

There are several implications associated with these findings. Geyser formation in this tunnel system is not directly connected with surging in the tunnel system. Numerical models that are currently applied to simulate transients in rapidly filling tunnel systems do not generally account for the air phase. The results of these models should be interpreted with caution. Predictions that transient hydraulic grade lines remain below grade should not be used to suggest that geyser formation will not occur. Model capability to predict the location of air entrapment within a system is useful, even if the subsequent motion of the air cannot be predicted with a single phase flow model. This information can be used judiciously to make design decisions about the location and capacity of air ventilation required in a system. We continue to investigate various aspects of this problem in order to be able to develop more detailed guidance for the design of such systems.

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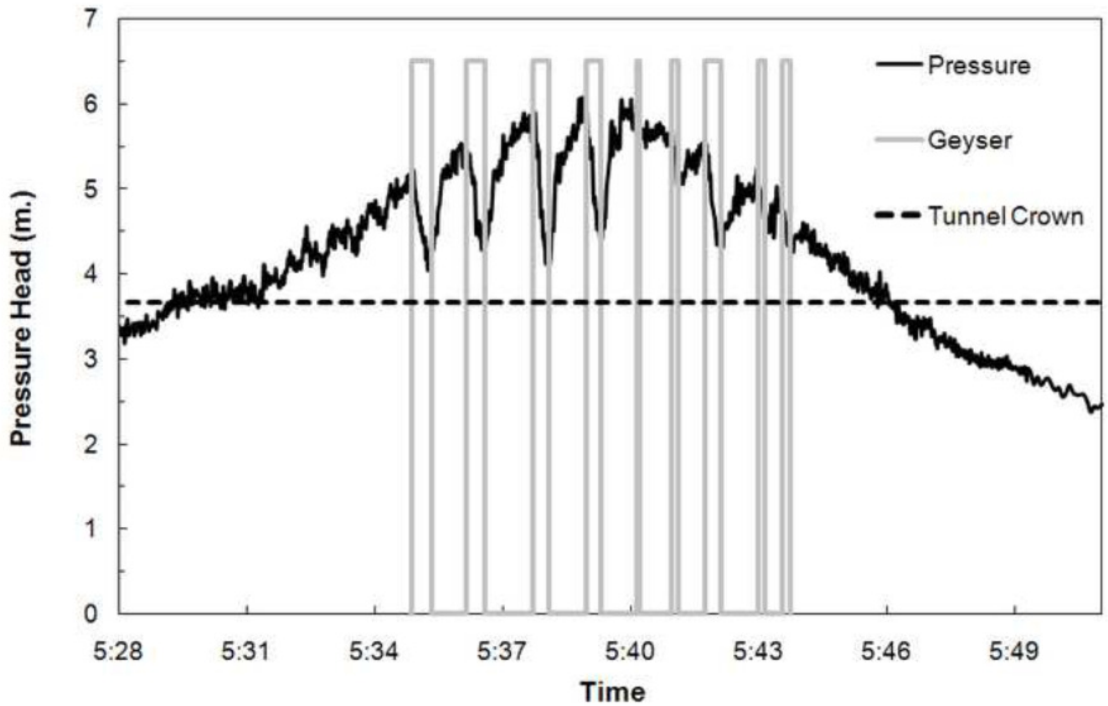
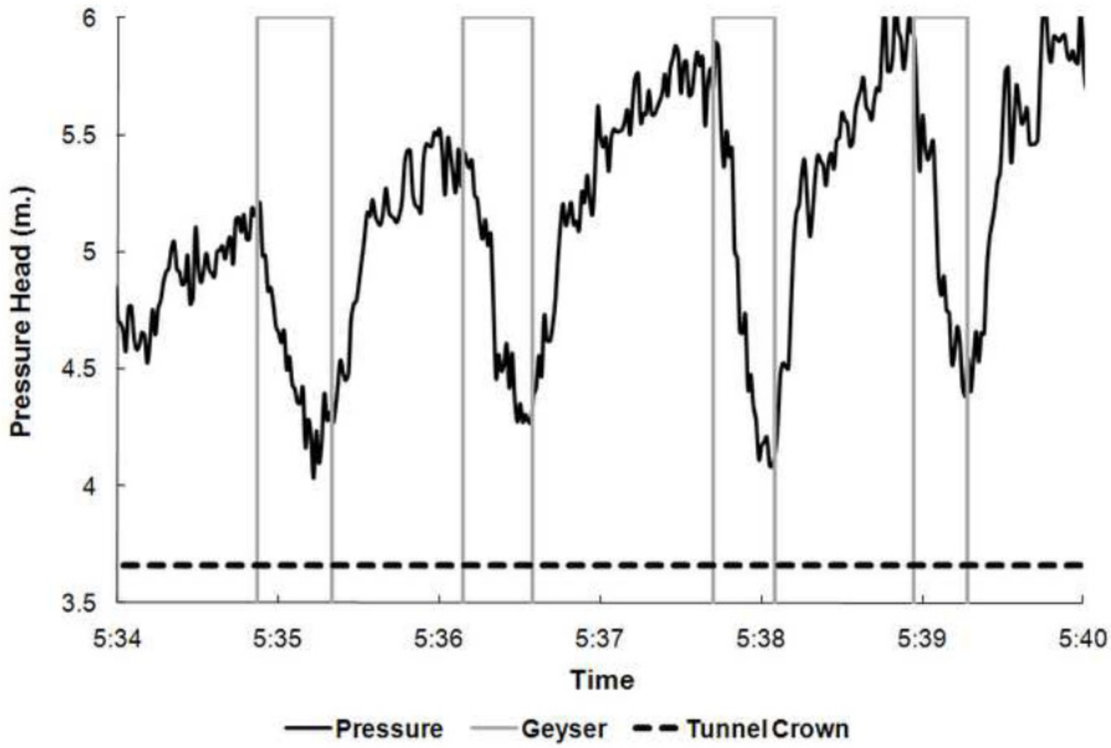
FIGURES

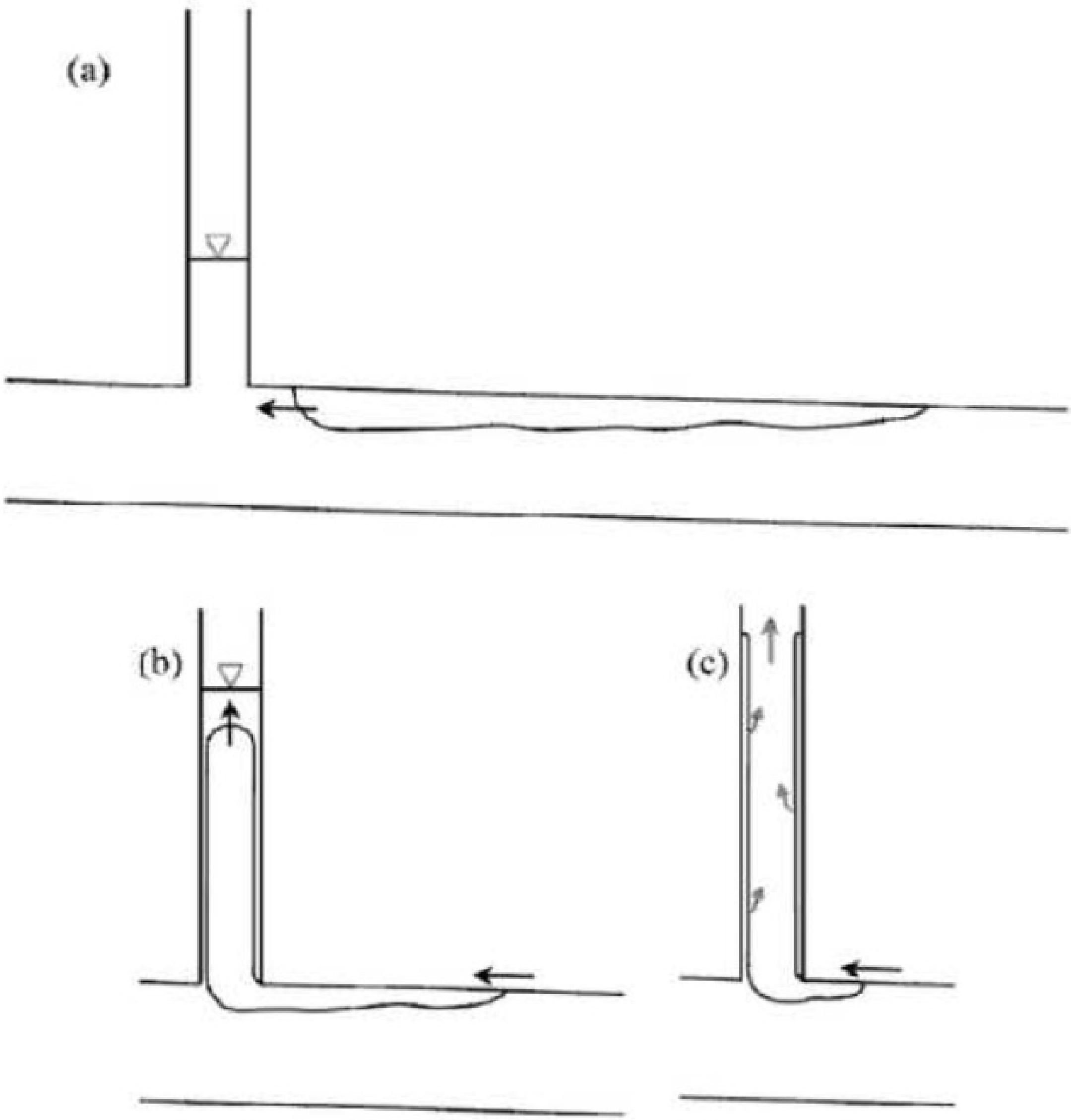
1	Image from a videotape of a geyser event occurring at a manhole in a stormwater tunnel in Minneapolis, Minnesota.



2	Pressure head relative to tunnel invert in tunnel recorded during geyser event of July 11, 2004. Geyser events begin at 5:35:11, 5:36:28, 5:38:01, 5:39:16, 5:40:27, 5:41:16, 5:42:03, 5:43:19, and 5:43:51 am.



3	Details of pressure variations during geyser.



4	A conceptual sketch of geysering due to the release of a large air pocket: (a) The large air pocket migrates towards the vertical shaft. (b) The momentum of the air pocket into the vertical shaft due to buoyancy causes the water level to rise. (c) The high velocity air flow may entrain liquid due to flooding instability. .