Summary of "Geyser" Research Experiments Conducted in the Fall of 2008 at the University of Michigan Hydraulics Lab

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Introduction

An experimental investigation continuing the previous studies of geyser events that occur in rapidly filling CSO (combined sewer overflow) storage tunnels was conducted. Geyser events occur when a mixture of air and water is explosively released upward through a vertical shaft. Previous investigation has revealed that the role of large air pockets is very significant in determining the severity of geyser events. Recent experiments conducted at the University of Michigan in the fall semester of 2008 were focused on four main objectives:

- Observe the migration behavior of large air pockets.
- Understand which air release scenarios are most problematic.
- Investigate further the concept of a diameter expansion within the vertical shaft to reduce geyser strengths.
- Explore the limitations in scaling the results from the laboratory setting to a prototype size.

A schematic of the experimental setup used for this study is presented in Fig. 1. The horizontal main tunnel consisted of 20 feet of 3.75 in-diameter clear acrylic pipe. A constant head reservoir tank was located upstream to control the inlet conditions. Air was injected through a small hose located at the pipe invert near the upstream end. The water flow rate was measured at the downstream outlet by performing three repetitions of collecting a weight of water and a measured time. A quarter-turn butterfly valve and a threaded PVC cap were located at the downstream end to regulate the flow through the tunnel. Two pressure transducers (Endevco model 8510B-1) were located as shown in Fig. 1 to monitor the pressure variations within the system. The vertical riser is located near the downstream end of the tunnel and is also made of clear acrylic pipe. The riser diameters varied between 0.5 in. and 5.25 in.

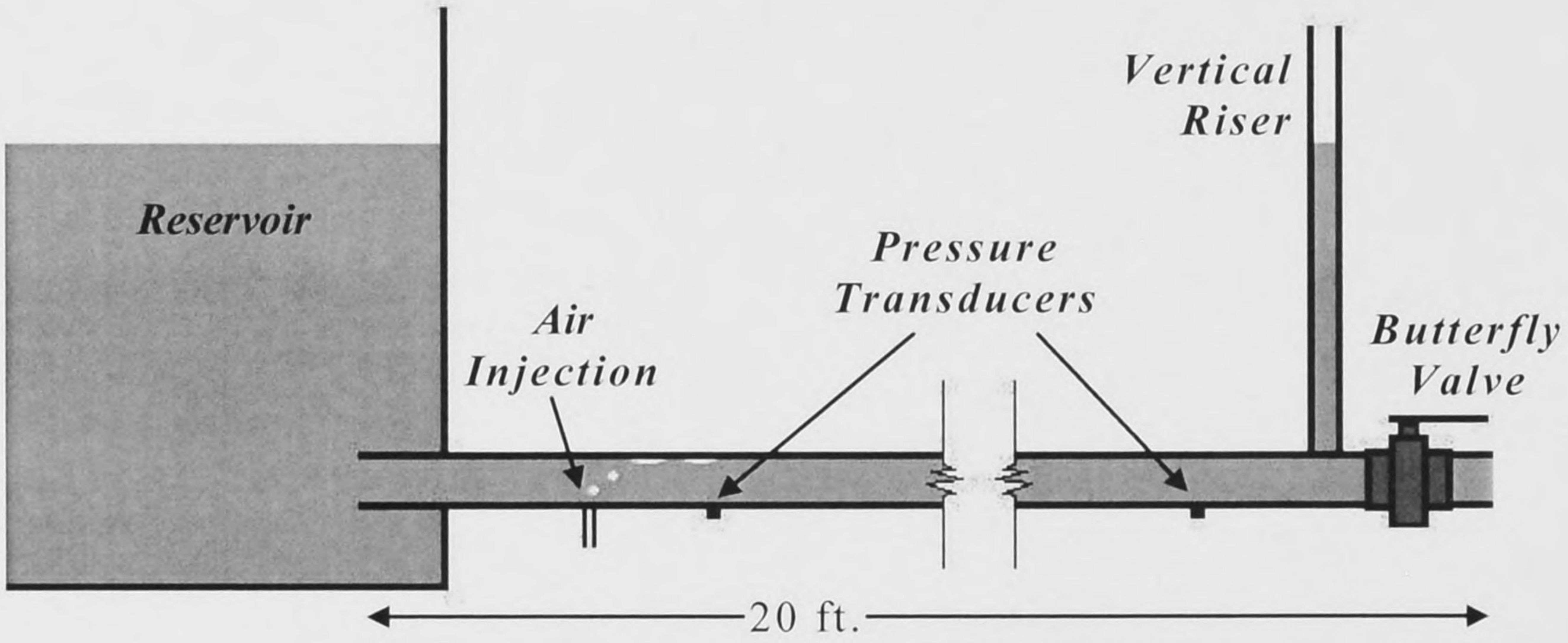


Figure 1: Schematic of Experimental Setup

In the field, the term *geyser* is generally used to describe an upward rise of liquid in a vertical shaft beyond the ground surface elevation, but in general this vertical location varies between systems. The goal of this study is to aid in the design process of general stormwater collection systems, and therefore it is important to qualify the phenomenon of geysering independent of a system's grade elevation. For this study, geysering is qualified as any vertical increase in liquid level (relative to the resting water level) greater than twice the main tunnel diameter due to the release of air.

General Observations:

Taking advantage of the clear acrylic pipe walls, the general behavior of the air and water was readily observed and recorded with a digital video camera capable of 30 frames per second. Following are a number of general observations from the experiments conducted in this study:

- Geyser events can occur from air injection only, i.e. no water flow is required. This suggests a general distinction between air-induced events and inertial surges that are generally invoked as an explanation for geyser formation.
- Air-induced geyser strengths are somewhat challenging to measure consistently. The water level in the vertical shaft is continuously oscillating, and the amplitude covers a large range. The strategy implemented for measuring the geyser strength during these experiments was to record the maximum water level observed in the riser shaft over the period of a few minutes for each set of experimental conditions.
- Small air pockets produce weaker geyser strengths, even when they occur in a rapid series. This can be explained by the ease of which the air and water are able to flow past each other within the vertical shaft. Small air pockets can rise in the vertical shaft without filling the majority of the cross-section; this situation does not require a significant displacement of the water in the shaft by the rising air. However, large air pockets are capable of swiftly accelerating a slug of liquid in front of them to a high upward velocity.
- The large air pockets are the most problematic for causing geyser events, especially when slug-behavior develops. Discrete "slugs" of water (or air/water mixtures) can develop within the vertical column as a sequence of large air pockets rise. These slugs can gain significant velocity as they are forced upward by the rising air. The large air pockets occupy the center of the vertical column as they rise and a thin film of downward water flow develops around the outside of the air. The height of rise of the water within the vertical shaft is determined by how quickly it can flow around the outside of the buoyant air bubble.
- Little change was detected in the geyser strengths between vertical riser diameters of 0.5, 1.0, and 1.75 in. For a 23 ft diameter tunnel, the tested riser diameters would scale to be: 3.1 ft, 6.1 ft, and 10.7 ft. Further research should be performed to verify the lack of influence of this variable.
- The geyser strength is increased by a higher initial water level within the vertical shaft. As a large air pocket arrives at the base of the riser, the entire column of liquid feels the buoyant force upward. As discussed above, the larger volume of

water will take longer to dislocate around the outside of the rising air pocket, resulting in a greater vertical rise.

Migration of Air Pockets:

Large migrating air pockets within the horizontal pipe were observed to have a distinct shape as shown in Fig. 2 consisting of a nose, a transition region (or wake / hydraulic jump), and a tail. The leading edge of the air pocket had a front or round head which typically was the thickest part of the air intrusion. A transition zone usually occurred for large air pockets located just behind the nose region. This can be thought of as a wake zone due to water flowing around the front of the air pocket; sometimes forming a distinct hydraulic jump. Next, the body of the air pocket generally stretched out along the crown of the pipe to form a long, narrow tail. Surface waves occurred in this region of the air flow and occasionally these waves reached all the way to the crown of the pipe, breaking the air pocket into separate bubbles. Under certain circumstances, such as when the pressurized air pocket began to escape, the end of the tail region developed into a front similar to a pipe-filling bore. The development of this front also created a significant surge potential due to the inertia of the advancing water column so that surges in the vertical shaft could be observed both when the air pocket initially reached the shaft and then again when the tail end of it was expelled.

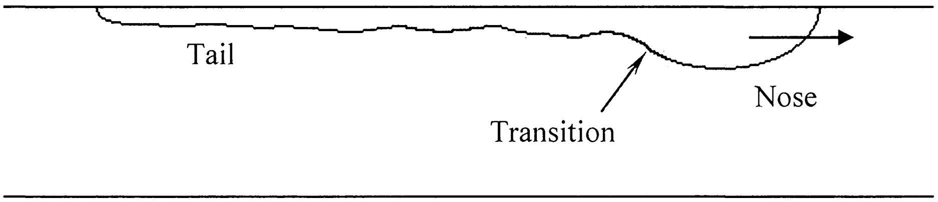


Figure 2: Shape of Large Migrating Air Pocket

The experiments revealed that larger air pockets migrated with higher velocities than smaller ones. Also, as the air pockets caught up to one another, they coalesced rather easily to form a combined pocket. The air pockets even accelerated to speeds greater than the moving water velocity. The study by Benjamin (1968) revealed that air intrusions for emptying, horizontal, circular pipes can reach speeds of $0.93\sqrt{(gD)}$, where g is the gravitational acceleration and D is the pipe diameter. This value corresponds to an emptying pipe scenario in which an infinite air intrusion is traveling in the opposite direction of the water flow. A study by Little et al. (2008) confirms this equation for the water velocity required to fully displace air forward. Air pocket velocities could exceed this value when traveling in the same direction of water flow. However, taking the mean water velocity as the frame of reference, the Benjamin equation seems to provide an upper bound for how fast the air pockets can migrate. Figure 3 below shows the measured properties of migrating air pockets and the complete data are presented in Table A-1 of the appendix to this report. Although the velocity of the air bubble does exceed that of the water flow, it does not approach that relative velocity suggested by the Benjamin analysis; this is apparently due to the fact that the air and water are moving in the same direction and the general assumptions in the Benjamin analysis are not satisfied.

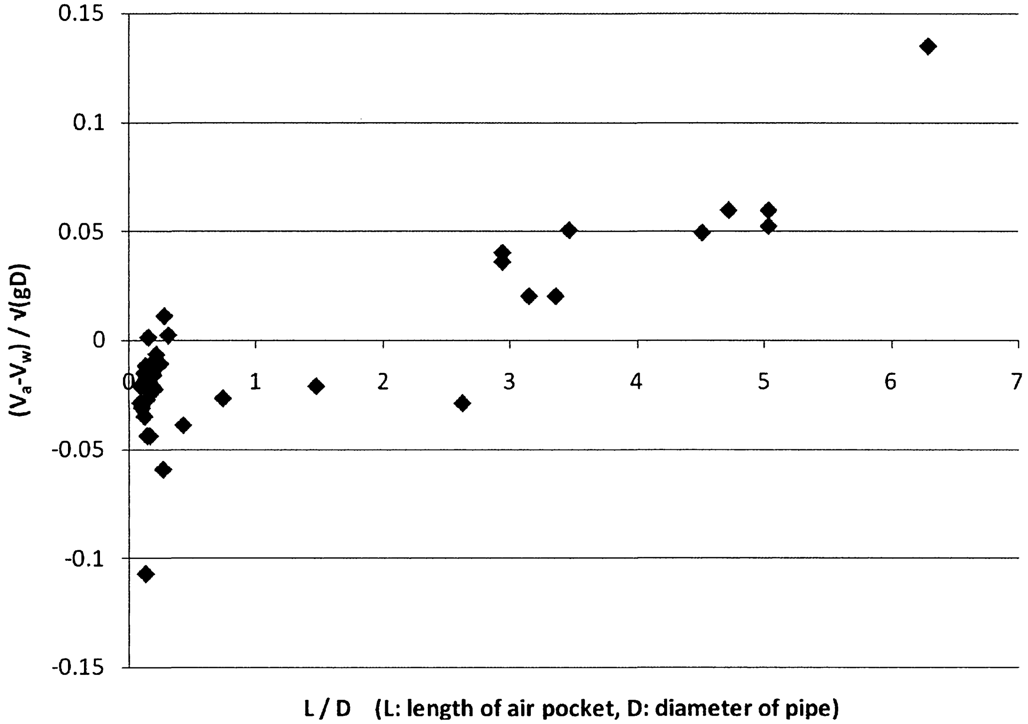


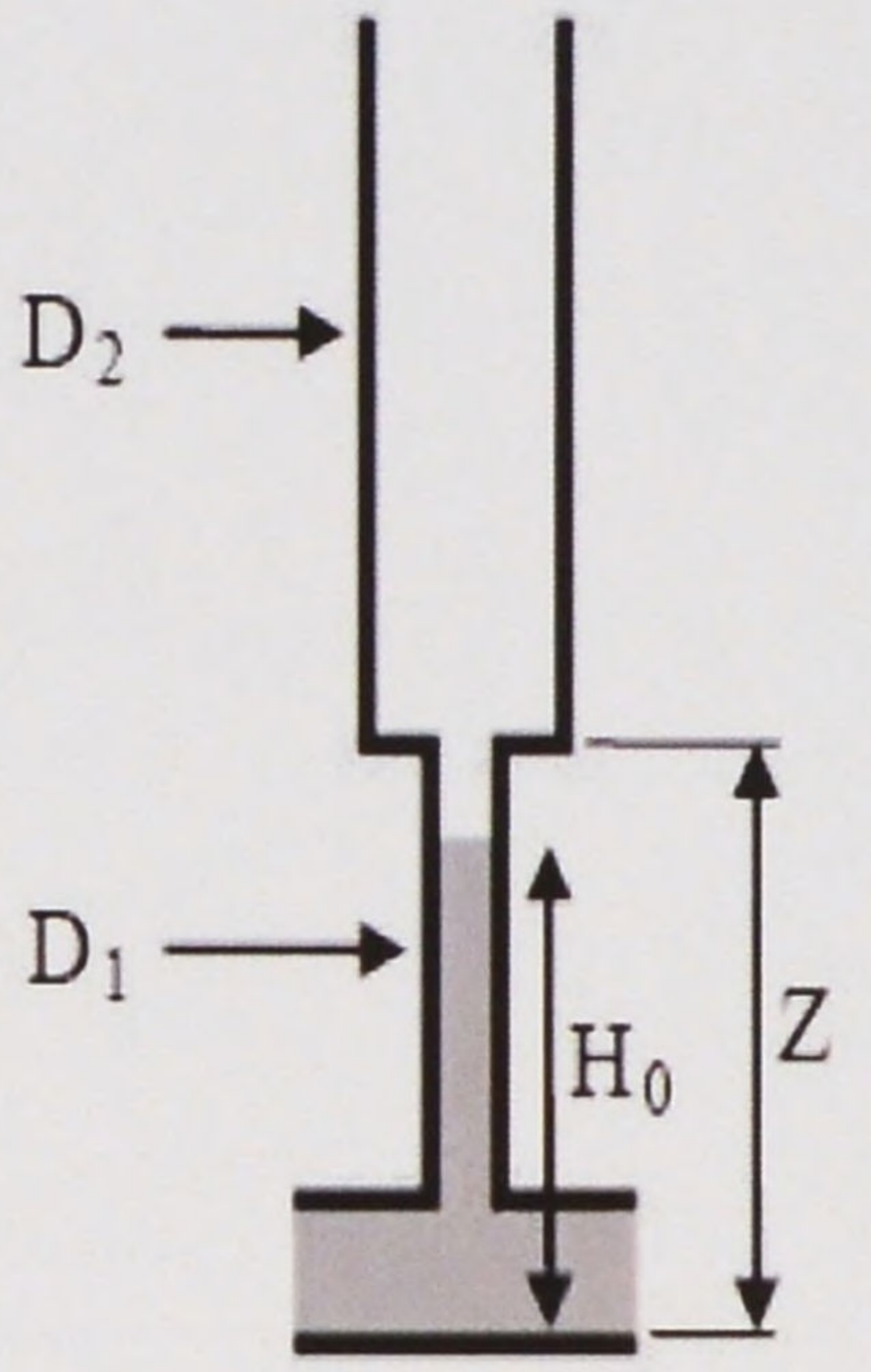
Figure 3: Air Pocket Migration Data

Geometric Adjustments:

Mitigation of geyser events could potentially be achieved by disrupting the interaction between the upward accelerating air slug and the thin film of downward water flow around the outside. One method to accomplish this is to construct a diameter expansion within the vertical shaft as shown in Fig. 4. This concept is presumed to be primarily influenced by two variables: the ratio of diameters at the expansion and the vertical location of the expansion. The experimental results are presented in Table A-2 and Fig. 5 below.

The diameter expansion experiments indicate successful mitigation of the geyser event under certain conditions. The low air inflow rate 0.136 L/s resulted in a geyser strength of 78 cm for the control test. The expansion ratios of 1.29, 2.14, and 3.00 constructed at a vertical location of 40.3 cm reduced the geyser strengths to 58, 45, and 44 cm, respectively. The two larger expansion ratios resulted in water levels that only reached a small distance above the expansion.

The high air flow rate 0.87 L/s resulted in a geyser strength of 152 cm for the control test. The diameter expansions were installed at a vertical location of 40.3 cm. The expansion ratios of 1.29, 2.14, and 3.00 reduced the geyser strengths to 101, 71, and 61 cm, respectively. In subsequent experiments, the diameter expansions were installed at a vertical location of 101.3 cm. The diameter expansions were unsuccessful in reducing the strength of the geyser in any of the measurements. It is important to note



Where:
D_1 = riser diameter below the expansion
D_2 = riser diameter above the expansion
Z = vertical location of diameter expansion
H_0 = initial water level

Figure 4. Schematic of Riser Diameter Expansion and Variable Descriptions

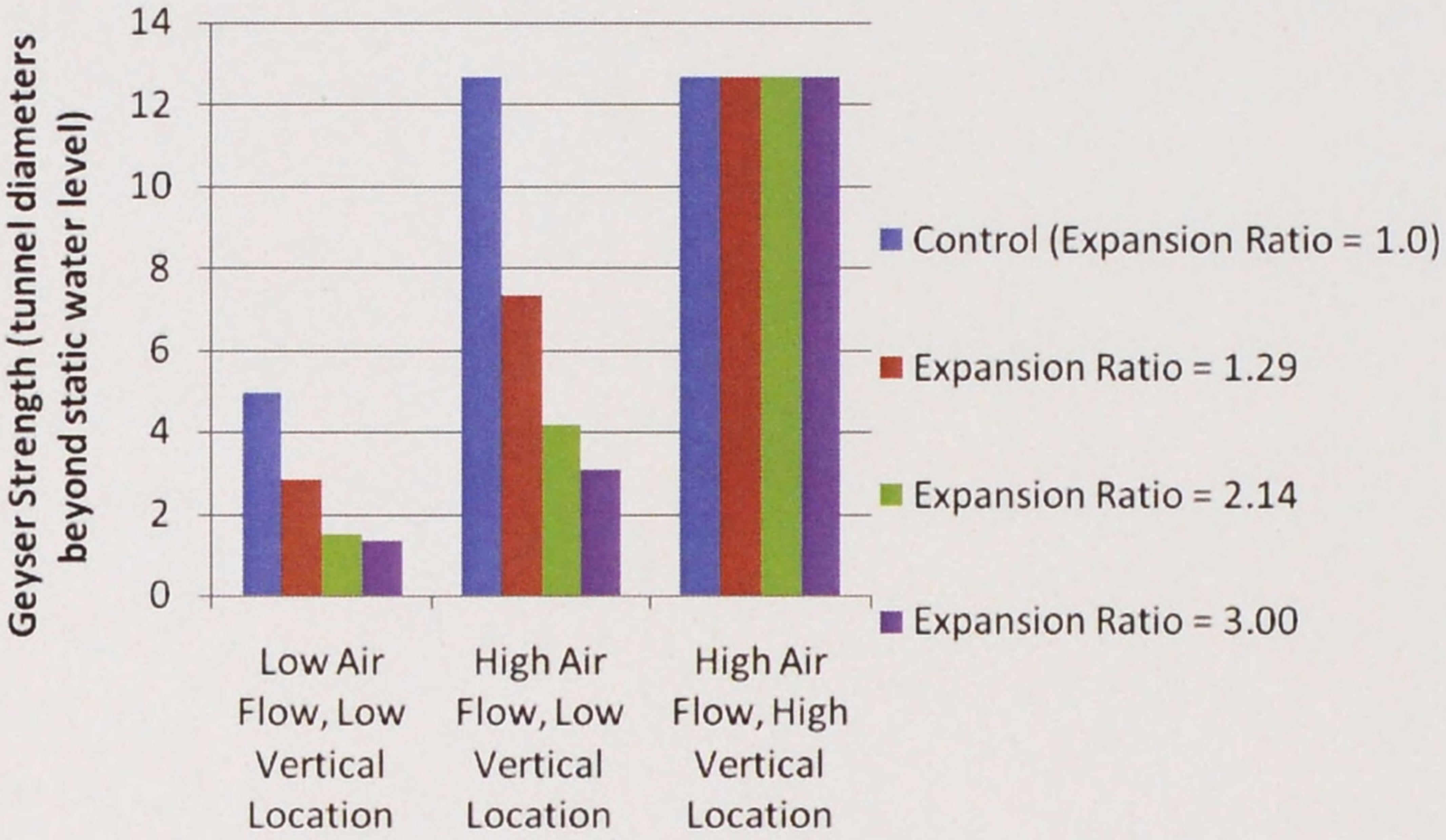


Figure 5. Geyser strengths for diameter expansion experiments.

that the geyser rise for the higher vertical location was not identifiable as a horizontal water level but rather a spray height within the shaft. Overall, geyser strengths were reduced successfully for the vertical location of 40.3 cm but unsuccessfully for the vertical location of 101.3 cm.

There seems to be a vertical location within the shaft where the air/water mixture reaches a peak velocity and begins decelerating. Placing an expansion above this location will do very little to solve geyser problems. In other words, constructing a diameter expansion just below the ground surface will not significantly reduce the geyser strength. The vertical placement of the diameter expansion should be well below the location where the maximum velocity is reached in order to reduce the peak upward velocity, and thus reduce the geyser strength.

Scaling Effects:

The same overall experimental setup was constructed for the larger scale experiment. The tunnel diameter was increased from 3.75 inches to 8 inches, a scaling factor of 2.13. A small number of preliminary tests were performed using the same conditions as used for the small-scale experiments. The air flow rate was increased based on Froude number scaling between the two sizes. The results in Table 3 below show that the geyser rise is less than the scaling predictions would expect. The air-induced geyser rise was roughly the same in the two sets of experiments and one would expect the rise to be larger in the large-scale experiment by a factor of 2.13. Although further tests on the larger scale system still need to be performed, the same general observations were made although the results do not appear to follow dynamic similarity considerations based on Froude Number similarity. In other tests, geyser strengths of over 6 feet occurred in the 8" pipe experiments for certain filling scenarios, but a complete data set is still being developed.

Table 3: Scaling Effects

Tunnel Diameter (in.)	Air flow (L/s)	Water flow	Riser Diameter (in.)	Geyser rise (in.)
3.75	0.136	0	1.75	31
8	0.87	0	3.75	33

Conclusions and Further Work:

Air Migration:

A trend can be seen from the air migration data which shows an increasing velocity as a function of the air pocket size. However, as the data levels off there seems to be an upper limit for air migration. This realistic migration velocity may be related to the infinitely long air intrusion relation of Benjamin applied to the frame of reference of the mean water velocity. More data will be collected for both pipe diameter sizes in order to check this hypothesis. It will also be helpful to perform experiments in which the pipe has a small downward slope and a small flow down the slope in order to see what conditions are required in order for air pockets to migrate upstream against the water flow.

Vertical Diameter Expansion:

The set of data for the 3.75" diameter pipe indicates an optimal expansion ratio of roughly 2.1 (the expansion ratio needs to be greater than this amount to result in significant reduction in geyser strength) and a vertical location of the expansion at a height of roughly 4 diameters above the pipe crown at the laboratory scale. Further study of these parameters is required before general design guidelines can be suggested. Overall, the experiments successfully showed that the diameter expansion is highly effective as long as it is below a certain vertical location. The same procedure will be performed in the 8" diameter pipe for comparison. It is unclear whether the initial water level is a significant variable for these tests, so that will also be adjusted and observed.

Scaling:

More experiments will be conducted in the 8” diameter pipe. A problem of inadequate air injection rate was encountered for the larger pipe but can be resolved by modifying the experimental setup. Air pocket velocities will be measured and compared with the results from the 3.75” diameter pipe results. As stated above, the diameter expansion tests will be performed to determine whether this approach is equally successful in reducing geyser strengths in the 8” pipe. The Froude Number scaling method may need modification to establish correct scaling relations for these scenarios.

References:

Benjamin, T. B. (1968). “Gravity currents and related phenomena.” J. Fluid Mech., Volume 31, Issue 2, pp. 209–248.

Little, M.J., Powell, J.C., Clark, P.B. (2008). “Air Movement in Pipelines – some new developments.” 10th International Conference on Pressure Surges. Edinburgh, UK. BHR Group Ltd. pp111-122.

Appendix:

Table A-1: Air Bubble Velocities

Length of Bubble (cm)	Bubble Velocity (cm/s)	Water flow (cm^3/sec)	Area of Pipe (cm)	Mean Water Velocity (cm/s)
2	10.10	765	71.26	10.74
1.9	9.81	765	71.26	10.74
1.2	9.59	765	71.26	10.74
1.4	9.53	765	71.26	10.74
1.1	9.27	765	71.26	10.74
1.8	9.18	765	71.26	10.74
2.9	10.95	765	71.26	10.74
1.3	9.14	765	71.26	10.74
1.2	8.76	765	71.26	10.74
43	15.50	765	71.26	10.74
48	15.79	765	71.26	10.74
33	15.62	765	71.26	10.74
28	14.61	765	71.26	10.74
1.1	20.06	1671	71.26	23.45
0.8	21.42	1671	71.26	23.45
1.3	21.32	1671	71.26	23.45
1.7	21.42	1671	71.26	23.45
1.3	21.74	1671	71.26	23.45
1.3	19.19	1671	71.26	23.45
0.9	20.43	1671	71.26	23.45
1.3	20.80	1671	71.26	23.45

1.9	21.26	1671	71.26	23.45
1.4	23.57	1671	71.26	23.45
0.8	20.66	1671	71.26	23.45
1.5	19.19	1671	71.26	23.45
2.3	22.40	1671	71.26	23.45
2.6	24.52	1671	71.26	23.45
30	25.40	1671	71.26	23.45
1.2	13.07	1671	71.26	23.45
32	25.40	1671	71.26	23.45
7	20.86	1671	71.26	23.45
28	26.92	1671	71.26	23.45
48	29.21	1671	71.26	23.45
2.5	17.70	1671	71.26	23.45
4	19.67	1671	71.26	23.45
45	29.21	1671	71.26	23.45
25	20.64	1671	71.26	23.45
14	21.40	1671	71.26	23.45
60	36.51	1671	71.26	23.45

Table A-2: Expansion Measurements

D_1 (cm)	D_2 (cm)	Expansion Ratio	Z (cm)	Air Injection (L/s)	Water Flow	H_0 (cm)	Peak Geyser Height (cm)
4.45	4.45	1.00	40.3	0.136	0	31.4	78
4.45	5.72	1.29	40.3	0.136	0	31.4	58
4.45	9.53	2.14	40.3	0.136	0	31.4	45
4.45	13.34	3.00	40.3	0.136	0	31.4	44
4.45	4.45	1.00	40.3	0.87	0	31.4	152
4.45	5.72	1.29	40.3	0.87	0	31.4	101
4.45	9.53	2.14	40.3	0.87	0	31.4	71
4.45	13.34	3.00	40.3	0.87	0	31.4	61
4.45	4.45	1.00	101.3	0.87	0	31.4	152
4.45	5.72	1.29	101.3	0.87	0	31.4	152
4.45	9.53	2.14	101.3	0.87	0	31.4	152
4.45	13.34	3.00	101.3	0.87	0	31.4	152

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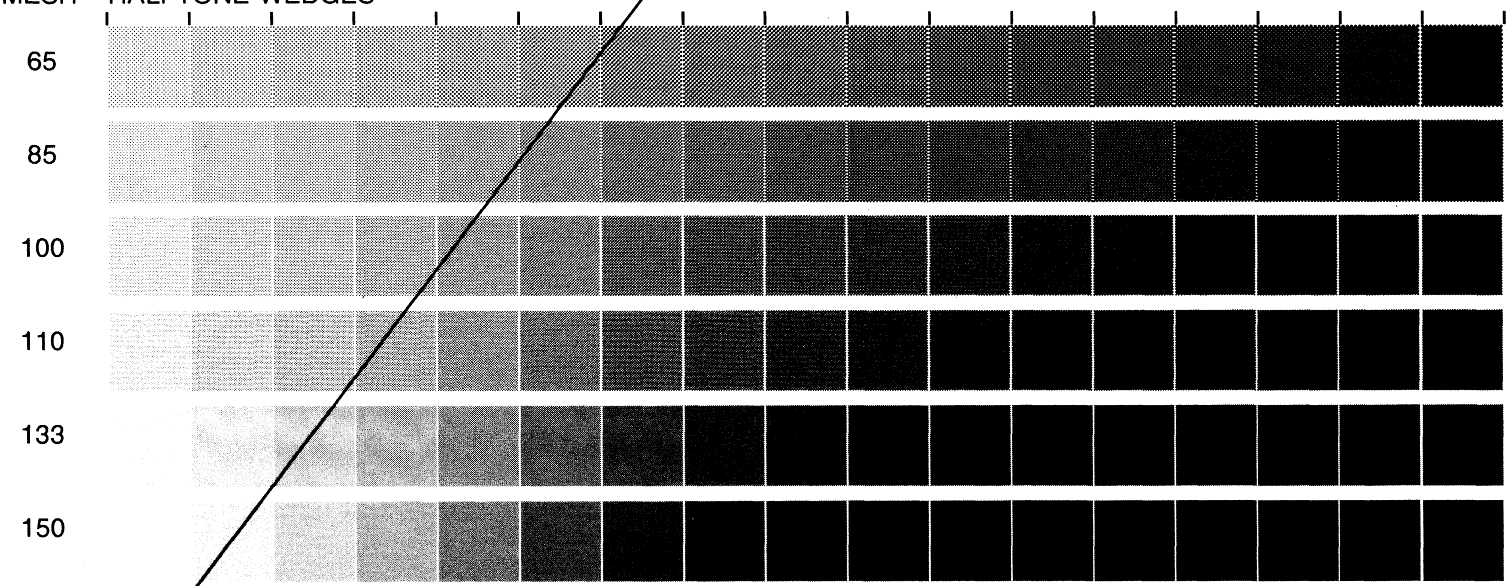

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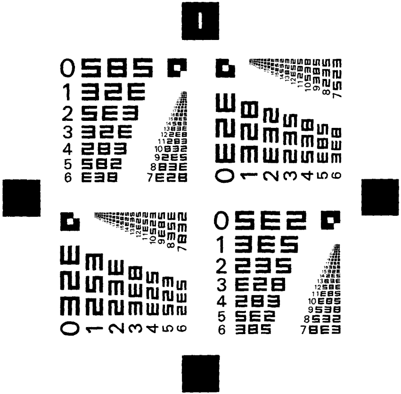

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