6th International Symposium on Hydraulic Structures

Jun 29th, 1:30 PM - 3:30 PM

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Effects of Hydraulic Jump Motion on Air Entrainment in Closed Conduits

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ABSTRACT

Air vent systems are designed to protect hydropower penstocks and reservoir outlets under various operating conditions. During an emergency closure of an upstream gate, the hydraulic jump that forms downstream of the gate is not stationary and may advance downstream, potentially increasing the total air demand. A lab-scale physical model of a general outlet works piping configuration was constructed at Reclamation's Hydraulics Laboratory in Denver, CO to observe hydraulic jump behavior during emergency gate closures. Parameters including gate discharge, gate closure rate, air vent size, and downstream pipe pressure were tested at two different pipe slopes. Results indicate that the hydraulic jump travel speed is dependent on air vent size as well as gate closure rate, both of which affect the internal pressure in the pipe near the vent connection. For a shallow-sloped pipe, the jump speed remains steady throughout the entire pipe length if the air supply is sufficient. However, if air flow is significantly reduced due to an undersized air vent, unsteady travel speeds and pressure surges were observed. This was not the case for a steep-sloped pipe, which produced steady jump speeds for all vent sizes. Once completed, these results are expected to be applicable for prediction of hydraulic jump travel speed and its effects on air demand for vent sizing considerations based on hydraulic operating conditions.

Keywords: *air entrainment, air vent, emergency gate closure, hydraulic jump, outlet works, penstock.*

1. INTRODUCTION

Air vent systems are designed to protect penstocks and low-level outlet pipes from excessively low pressures during emergency gate closures. An adequate air supply is necessary to allow smooth gate operation, prevent cavitation damage, and, in some cases, prevent pipe collapse. As the emergency gate closes, a hydraulic jump (jump) forms in the pipe, which may then travel downstream, drawing air as it moves due to entrainment and the air volume change in the pipe. Extensive work has been done on air entrainment for stationary jumps in closed conduits, including Kalinske & Robertson (1943), Sharma (1976), Falvey (1980), Escarameia (2007), and Mortensen et al (2011). Also, Parvaresh et al (2006) and Nasvi et al (2010) have conducted experiments on moving jumps in rectangular open channels. However, there is limited information in the literature that addresses moving jumps in closed conduits.

The main objective of this study is to determine the travel speed of jumps in closed conduits due to an upstream gate closure and its effect on the total air demand. For this study, total air demand is defined as the air flowrate entrained by the jump plus the air flowrate required to fill the evacuated pipe volume as the jump moves downstream. This study focuses on the latter component, which will further aid in the design and sizing of air vent systems for penstocks and outlet pipes. As infrastructure ages and operational requirements change, it becomes increasingly important to accurately predict air demand for adequate sizing of air vent systems. Improvements in predicting jump movement are necessary to reduce the uncertainty of existing air demand prediction methods.

The results presented in this paper were obtained using a lab-scale physical model as part of an ongoing study at the Bureau of Reclamation's Hydraulics Laboratory in Denver, CO to improve analyses of air vent systems. The study includes collections of physical data from both the lab-scale model and future field testing at a Reclamation facility (not included in this paper). Data collection and analyses are expected to be completed in 2016. These data will be used to improve analytical methods (Falvey, 1980) and (Frizell, 1993) for air demand prediction to support optimized air vent sizing and design.

2. EXPERIMENTAL SETUP

The laboratory physical model is comprised of a 30.48 cm diameter pipe on 0.55- and 26.0-percent slopes as illustrated in Figure 1 and Figure 2. The arrangement consists of a slide (emergency) gate at the upstream end, which is operated with a variable speed motor, followed by a 7.62 cm clear PVC air vent pipe immediately downstream. The main section is approximately 45 pipe diameters in length and made of clear PVC for flow visualization. Back pressure in the pipe was provided by a butterfly valve at the downstream end of the pipe.

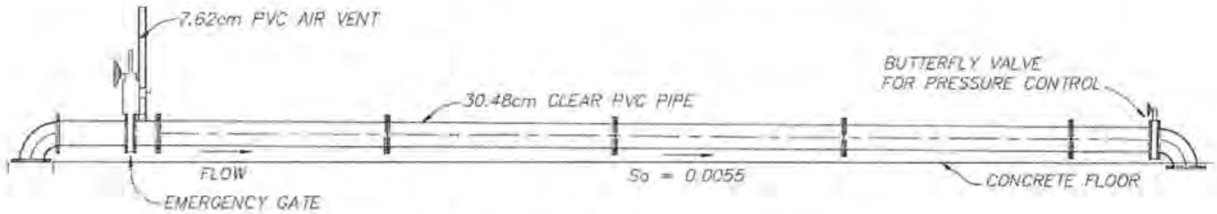


Figure 1. Profile view of 0.55-percent slope model.

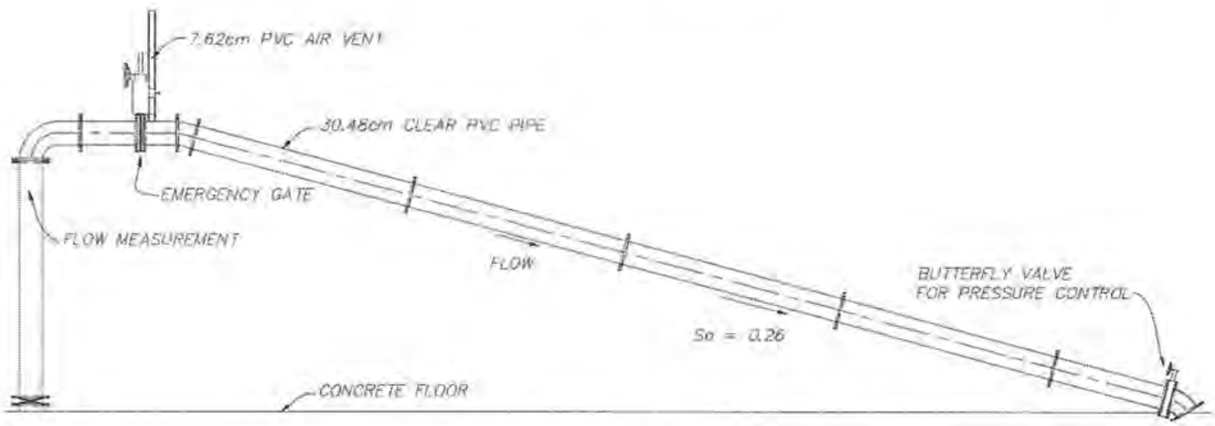


Figure 2. Profile view of 26-percent slope model.

Initial water flowrates, vent sizes, and gate closure rates were varied at each pipe slope as shown in Table 1. Flowrates were controlled with the lab's PLC pump control system. Initial laboratory tests produced maximum flowrates that were limited as a result of the steep pipe slope and higher inlet elevation, which increased head on the pump. Additional flowrates at the steep slope are currently being tested, and results will be available in the near future. The air vent size was varied by inserting a fitting with different orifice sizes at the top of the air vent pipe. Gate closure rates were controlled using the variable speed motor.

2.1. Test Procedure

Each test run began with a steady-state flow rate in the pipe before the emergency gate started to close. As the gate closed, the air vent was manually opened to allow air to flow into the pipe when the internal pressure downstream of the gate was sufficiently low to initiate venting. The pressure upstream of the gate was held constant throughout the test by adjusting the variable frequency drive on the pump as the gate closed to represent a constant reservoir head. As the gate continued to close, a jump would form downstream of the gate and eventually move downstream and out of the pipe. The downstream butterfly valve was left in a set position throughout each test run.

The instrumentation setup included an acoustic flowmeter (±2% accuracy) to measure water flowrate entering the laboratory setup, a string transducer (±0.25% accuracy) to measure gate position, an anemometer (±1.5% accuracy) to measure air velocity in the vent pipe, and absolute pressure transducers (±0.25% accuracy) to measure pipe pressures immediately upstream and downstream of the gate as well as at the downstream end of the pipe near the butterfly valve. All measurements were recorded at a sample rate of 500 samples per second. Local atmospheric pressure was obtained using a mercury barometer during each testing period. The average jump travel speeds were estimated using an HD video camera (30 frames per second) and visible station markers located along the test pipe.

Table 1. Operational parameters tested with the physical pipe model.

Pipe Slope	Vent Diameter Ratio	Gate Closure Rate	$^*Q_{stand}$
cm / cm	(D_{vent} / D_{pipe})	*(% Open) / sec*	$Q_{water}^2 / (gD^5)$
0.0055	0.25	0.76, 0.60, 0.34, & 0.10	3.94, 2.45, 1.30, & 0.52
	0.125	0.76, 0.60, 0.34, & 0.10	3.94, 2.45, 1.30, & 0.52
	0.094	0.76, 0.60, 0.34, & 0.10	3.94, 2.45, 1.30, & 0.52
	0.063	0.76, 0.60, 0.34, & 0.10	3.94, 2.45, 1.30, & 0.52
	0.042	0.76, 0.60, 0.34, & 0.10	3.94, 2.45, 1.30, & 0.52
0.26	0.25	0.76, 0.60, 0.34, & 0.10	3.09, 2.75, 1.83, & 1.27
	0.094	0.76, 0.60, 0.34, & 0.10	3.09, 2.75, 1.83, & 1.27
	0.063	0.76, 0.60, 0.34, & 0.10	3.09, 2.75, 1.83, & 1.27
	0.042	0.76, 0.60, 0.34, & 0.10	3.09, 2.75, 1.83, & 1.27

**Standardized water discharge at full gate opening - dimensionless flowrate equation and parameters are further defined on pg. 51 of Falvey (1980)*

3. RESULTS & DISCUSSION

3.1. Shallow Slope Pipe

Results show that air vent size has a significant effect on both internal pipe pressure at the vent connection and air flowrate through the vent, as expected (**Error! Reference source not found.Error! Reference source not found.**). **Error! Reference source not found.** shows that air vent size and gate closure rate also influence the travel speed of the moving jump. Vent ratios larger than 0.1 had an influence on travel speed by allowing the jump to move slightly faster in the larger vent sizes. This is most likely due to higher internal pipe pressures upstream of the jump due to the adequately-sized (prevents negative pipe pressure) air vent, effectively reducing the pressure differential across the jump and thereby reducing the resistance of the jump to move downstream. In this scenario, jump speeds were steady (no acceleration) from the time the jump formed in the upstream pipe near the gate until it left the end of the pipe downstream.

For vent ratios less than 0.10, the jump travel speed increased significantly (**Error! Reference source not found.**). Under such conditions, the jump would hold at a stationary point, usually near the upstream end of the pipe, until it finally released and rapidly moved down the pipe. Video documentation showed that the jump started to move when air that had previously accumulated downstream of the jump flowed back upstream, forcing the jump to quickly move downstream. The delay of the jump, and then its release and movement, were caused by initially negative upstream pressures caused by an undersized air vent. This process is shown in the time series photos in Figure 6.

Since air flow travelled back upstream, the incoming air flow through the vent decreased temporarily in the same gate position range for which jump movement occurred (**Error! Reference source not found.**). Also, the upstream pressure increased temporarily during initial jump movement (**Error! Reference source not found.**). Jump movement was often erratic and unsteady both before and after the burst of downstream movement. Data scatter in **Error! Reference source not found.** may be attributed somewhat to the difficulty in manually controlling pump pressure upstream of the gate but is largely due to the inherently erratic nature of jumps.

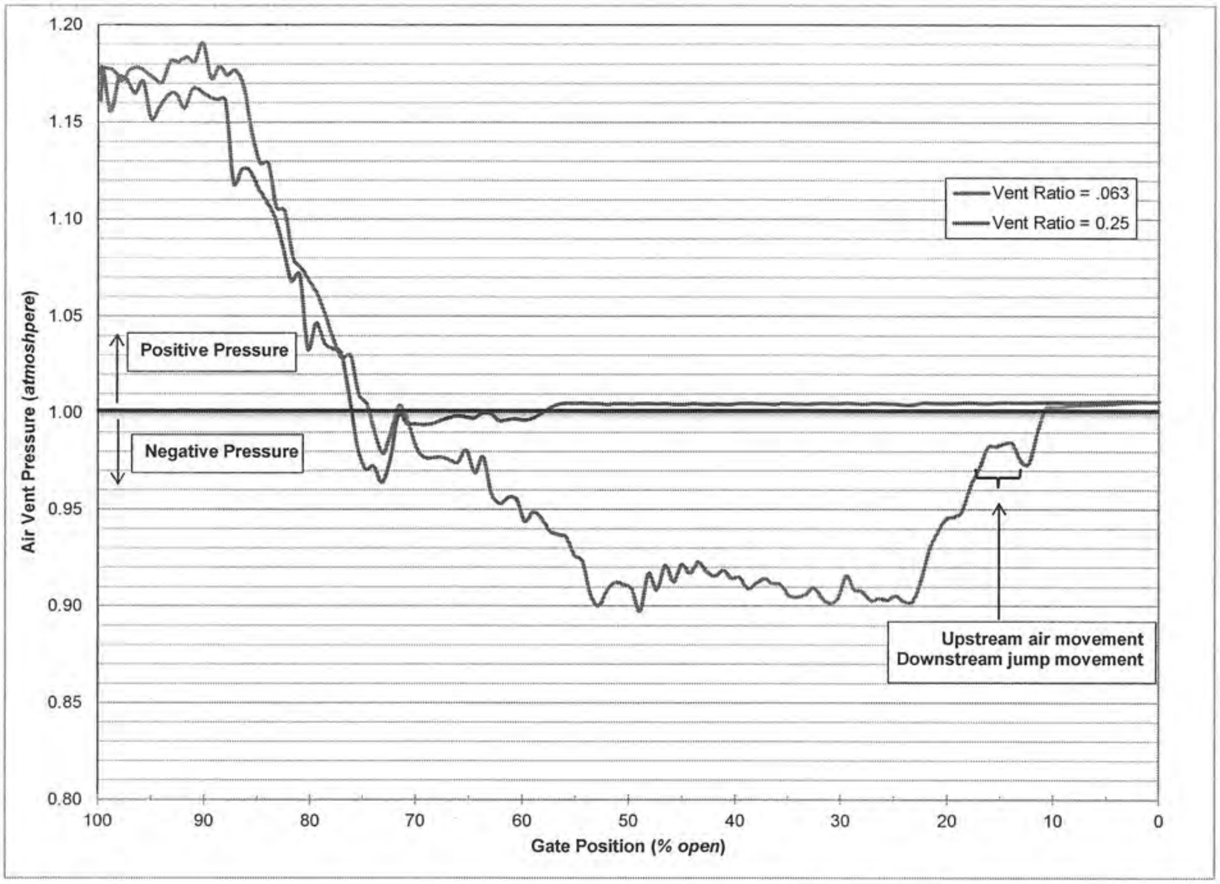


Figure 3. Air vent pressure vs. Gate position comparison of an adequately-sized (red) and undersized (blue) air vent. Pressure is standardized to local atmosphere indicating that pressure less than 1 atmosphere is negative.

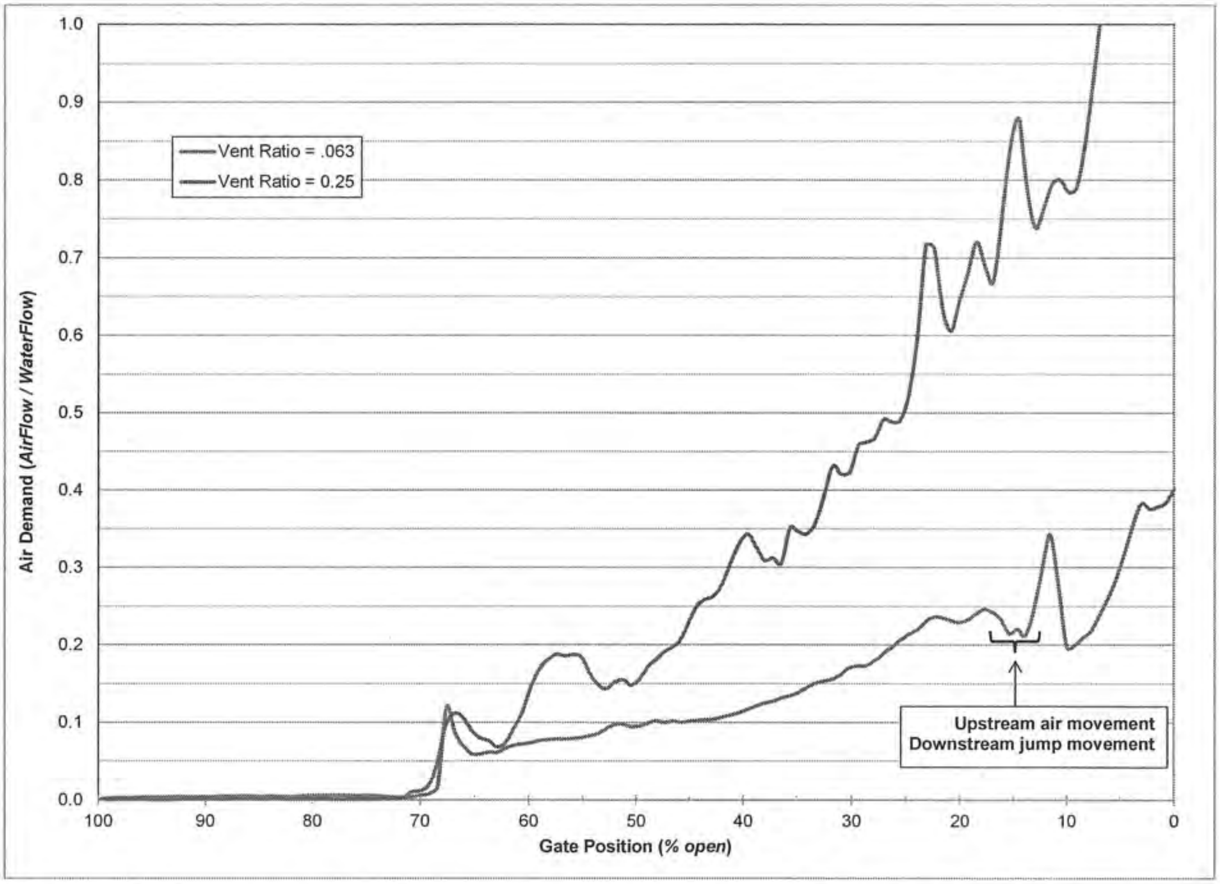


Figure 4 Air demand vs. Gate position comparison of an adequately-sized (red) and undersized (blue) air vent.

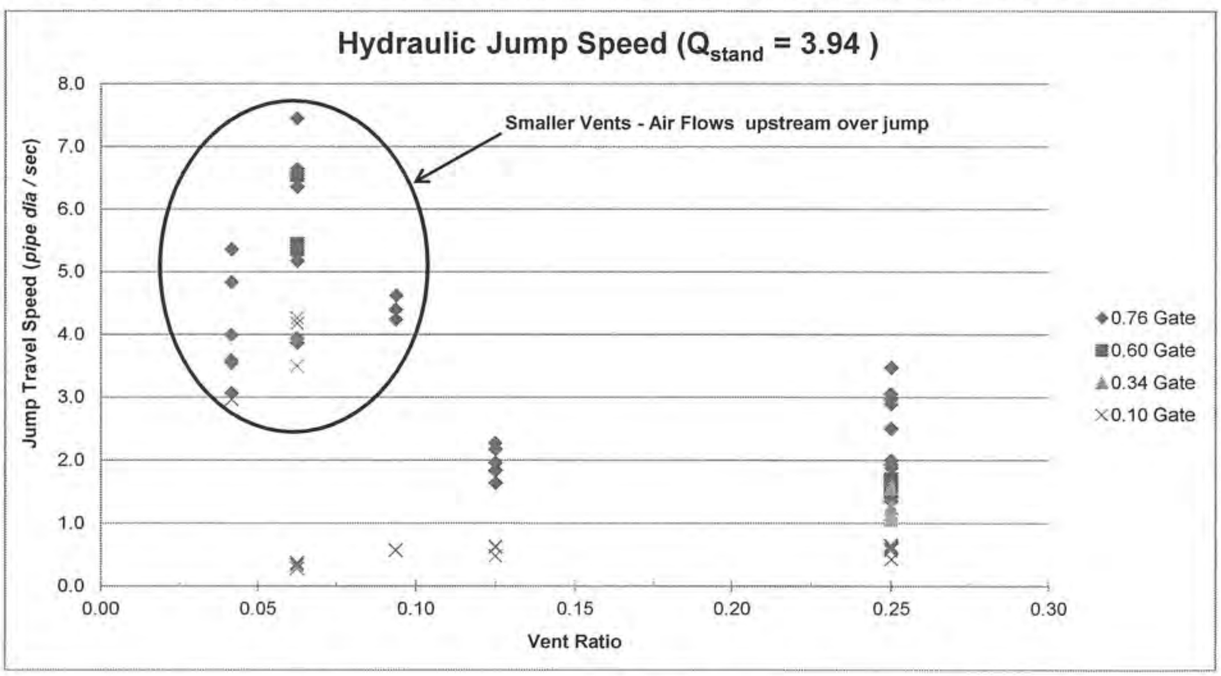
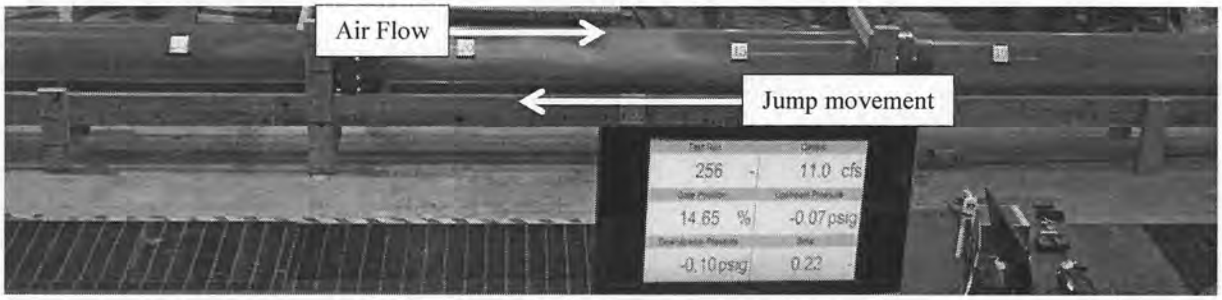


Figure 5. Jump travel speed vs. vent ratio for various gate closure rates on the shallow slope pipe.

(a)



(b)

(c)

Figure 6. Time series photographs of jump motion with an undersized air vent: (a) Jump is released and begins movement, (b) Jump moves downstream with air flowing back upstream, and (c) Jump is halted again further downstream in the pipe. Water flow and jump movement are from right to left.

3.2. Steep-Slope Pipe

As with the shallow slope, air vent size and gate closure rate also influenced the jump travel speed in a steep-sloped pipe, though there is still data scatter. **Error! Reference source not found.** shows the correlation of travel speed to vent size for all gate closure rates tested. The average of these data groups (Figure 8) helps clarify the effect of vent size for each gate closure rate tested. The most drastic change in jump travel speed occurs for vent ratios less than 0.10 except for the lowest gate closure rate where vent size has very little influence on travel speed.

A spike in travel speed at the smaller vent ratios has not been observed with the steep-slope. One explanation for this may be that the weight of the water column in and downstream of the jump at a steeper slope becomes a significant factor in the total momentum of the jump. The increased weight component of the momentum then overcomes the pressure differential component, which is large for smaller vent sizes, allowing continuous jump movement without halting. For data collected so far, the jump travel speed does not exceed 4 pipe diameters per second, which is similar to jump speeds measured at the shallow slope with adequately sized air vents. This information will be useful in estimating the total air demand by accounting for the air flowrate required to fill the pipe volume as the jump travels down the pipe.

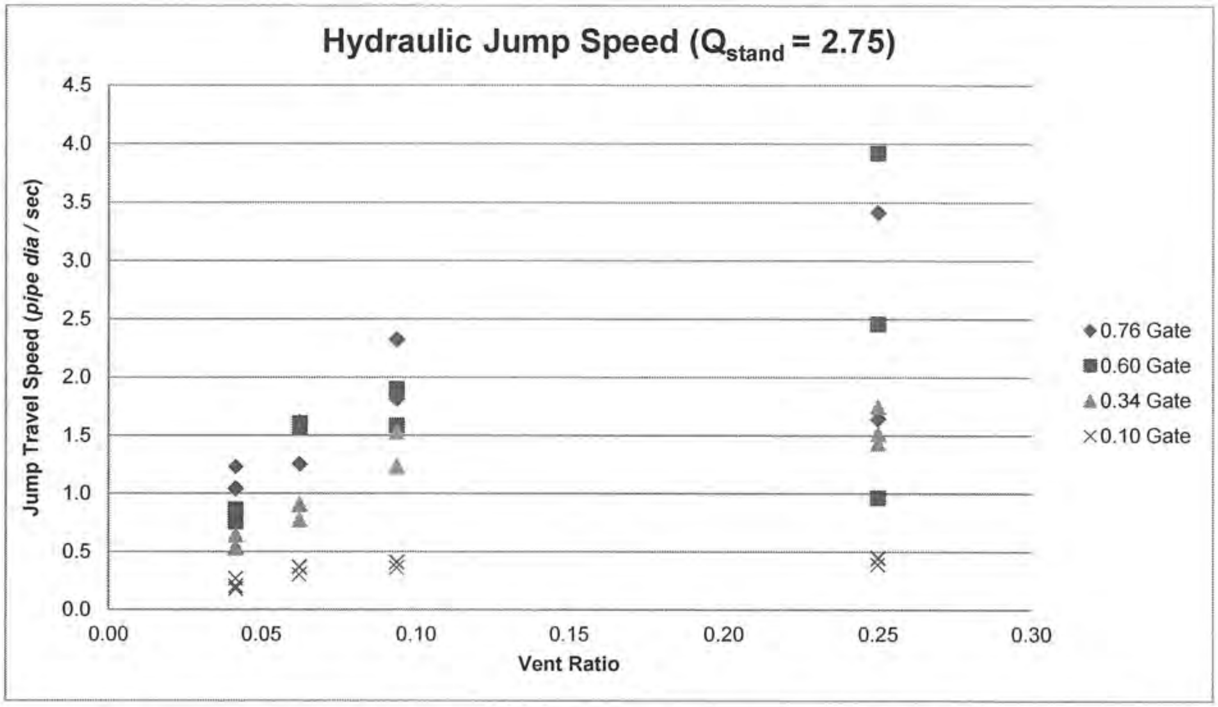


Figure 7. Hydraulic jump travel speed vs. vent ratio for various gate speeds on the steep-slope pipe.

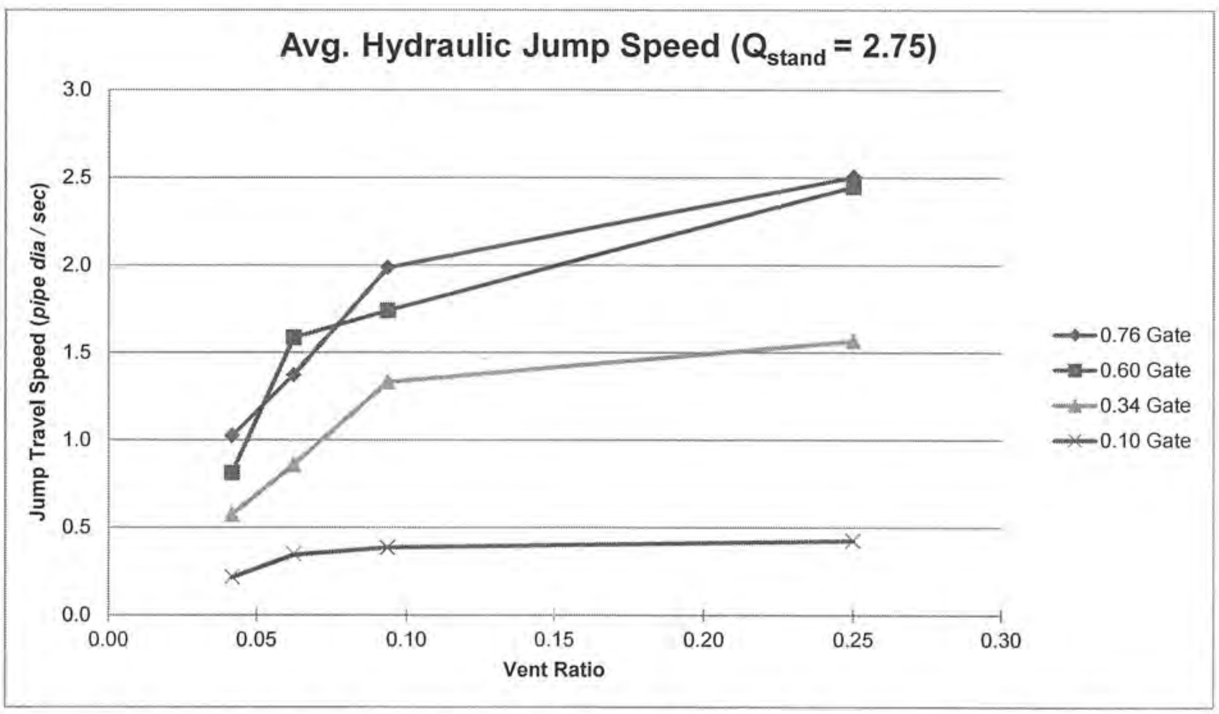


Figure 8. Average hydraulic jump travel speed from Figure 7 vs. vent ratio for various gate speeds on the steep-slope pipe.

4. CONCLUSIONS

The preliminary results of the laboratory physical modeling provide insight into the effects of hydraulic jump travel speed on the total air demand:

- Faster gate closing rates produced increased jump travel speed for both pipe slopes.
- For the shallow-slope pipe, adequately-sized air vents allowed faster jump travel speeds that remained steady (no acceleration) through the entire pipe length.
- For the shallow-slope pipe, jump speed was irregular and increased significantly when air flow was reduced by an undersized vent. This produced a large pressure difference across the jump, which caused accumulated air downstream of the jump to intermittently flow back upstream, causing the jump to release and move downstream at high speed. Air flow through the vent was decreased for this case despite increased jump speed.
- For the steep-slope pipe, jump speed remained steady for all vent sizes and the spike in jump travel speed observed in the shallow-slope pipe did not occur. Jump travel speed increased with both air vent size and gate closing rate.
- For both pipe slopes, jump travel speed never exceeded 4 pipe diameters per second.

Additional data collection from both the physical model and a field testing of an emergency gate closure are planned for later in 2016. The results are expected to help improve current analytical methods for air demand prediction in air vent sizing and design.

5. ACKNOWLEDGMENTS

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