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Managing Water in the West

Air Vent Analyses for Penstocks and Low-Level Outlets

Research and Development Office – S&T Program
Power Resources Office
Policy and Administration Office

(Final Report) ST-2017-1601-01

HL Report 2017-11

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2017

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REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
T1. REPORT DATE: SEPTEMBER 2017	**T2. REPORT TYPE:** RESEARCH	**T3. DATES COVERED** Nov. 2016 – Sept. 2017
T4. TITLE AND SUBTITLE Air Vent Analyses for Penstocks and Low-Level Outlets		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Josh Mortensen		**5d. PROJECT NUMBER** ST-2017-1607-01
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)		**8. PERFORMING ORGANIZATION REPORT NUMBER** HL-2017-11
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007		**10. SPONSOR/MONITOR'S ACRONYM(S)** **R&D:** Research and Development Office **BOR/USBR:** Bureau of Reclamation DOI: Department of the Interior
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) ST-2017-1607-01

12. DISTRIBUTION / AVAILABILITY STATEMENT
Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 words)*
Air vent systems help protect penstocks and low-level outlet pipes from the negative effects of emergency gate closures. Over the past 60 years Reclamation has studied emergency gate closures for closed conduits and developed numerical approaches to predict air vent sizing for air-water flows. This report summarizes efforts to restore and update numerical models from previous Reclamation research and documents findings from recent physical modeling efforts which define a relationship in which the speed of a moving hydraulic jump (or falling water surface) can be predicted.

15. SUBJECT TERMS
Air vent, air valve, air entrainment, emergency gate closure, low-level outlet, penstock

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT** **U**	**18. NUMBER OF PAGES** 34	**19a. NAME OF RESPONSIBLE PERSON** Bob F. Einhellig
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U			**19b. TELEPHONE NUMBER** 303-445-2142

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

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Research and Development Office – S&T Program
Power Resources Office
Policy and Administration Office

Hydraulic Investigations and Laboratory Services, 86-68560

(Final Report) ST-2017-1601-01

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Air Vent Analyses for Penstocks and Low-Level Outlets

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Acknowledgements

I need to recognize Jimmy Hastings, Jason Black, Dane Cheek and Marty Poos from the shops for their superb construction, installation, and maintenance of both laboratory physical models.

I also thank Tony Wahl, Joseph Kubitschek, and Warren Frizell for their technical guidance and significant effort with the numerical programs, as well as the many rotation engineers and interns who helped with the laboratory testing.

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Executive Summary

The physical pipe model, which included an emergency gate and air vent, provided valuable data from dynamic emergency gate closure tests to support further development of improved methods for air vent analyses. Primary conclusions include:

- A relationship for predicting the speed of a moving hydraulic jump as a function of initial water discharge, diameter, and gate closure time was found. These parameters can be used to predict the speed of the hydraulic jump for pipe slopes up to 26 percent.

- The relationship for hydraulic jump speed prediction assumes the air vent is adequately sized. Results showed that undersized vents produce negative pressures in the pipe which can influence jump speed, particularly in shallow slope pipes.

- Test results suggest that, compared to a stationary hydraulic jump, air entrained through the jump is decreased when the jump is moving downstream. Further analysis of the existing data set is needed to relate rate of air entrainment with hydraulic jump speed.

Three different numerical programs have been restored and updated. More detailed documentation including source code and user instructions specific to each program will be forthcoming.

- Falling Water Surface (Penstocks with turbines) – The FORTRAN code from Engineering Monograph No. 41 has been restored, updated, and compiled for use in Windows 7 (64-bit). It applies geometrical and hydraulic equations to a falling water surface in the pipe as the emergency gate closes. It is intended for hydropower penstocks with inputs for turbine characteristics. Results from the updated program compare well with those of previous versions which were compared to a field test at Morrow Point Dam.

- Method of Characteristics (Low-level Outlets) – A FORTRAN code was originally developed by Frizell (1993) from field and lab tests of low-level outlets, but the surviving version of the code was missing the proper boundary conditions for the air valve and downstream control gates. This information was added to the program, which was then converted to VBA, and is now available in spreadsheet form. This program is geared toward low-level outlets with shallow slopes. Results compare well with physical data from the laboratory model, although some minor adjustments are necessary.

- Hybrid Program – This code was written in Mathematica and uses the method of characteristics until air begins to enter the pipe. At that point the method of characteristics ends and the change in water volume and air entrainment through the hydraulic jump account for the total air demand. Results from the physical model showed that this approach likely overestimates the total air demand as the rate of air entrainment is significantly reduced for a moving hydraulic jump. This program is currently functional in Mathematica but needs further refinements.

- Field Testing Recommendation – It is recommended that field testing of an emergency gate closure be performed for comparison to numerical modeling. Reservoir and tail water elevations, water discharge, gate position, penstock pressures (immediately downstream of emergency gate and upstream of control or wicket gates), and air vent velocity should be measured. Potential opportunities include Green Mountain and Paonia Dams as their outlet works are currently under modification which required air vent calculations. Testing should be coordinated with TSC's Hydraulic and Mechanical Equipment groups.

Introduction

Air vent systems are designed primarily 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 prevent pipe collapse in some cases (Figures 1 and 2). As the emergency gate closes, at some point a hydraulic jump forms in the pipe, which then travels downstream, drawing air as it moves due to entrainment and the air volume change in the pipe. This complex and dynamic process makes it challenging to predict the required airflow (air demand) into the pipe and properly size the air vent.

Over the last 60 years Reclamation has conducted research on air-water flows in large pipes and developed a number of numerical methods to help predict airflow for proper air vent sizing (Falvey, 1968, Falvey, 1980, Frizell, 1993, and Kubitschek, 2014). While these numerical tools have been useful in the past some of them have become obsolete, either being written in outdated code language or not documented for general use. Each also has its limitations and uncertainties that require additional physical data for further development. Therefore, the two main objectives of this study include:

- Obtaining physical data to predict the movement of a hydraulic jump during an emergency gate closure.
- Update numerical methods previously developed by Reclamation to be readily applicable to current and future air vent sizing applications.

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 hydraulic jump movement are necessary to reduce the uncertainty of existing air demand prediction methods.

Figure 1 Example of a collapsed pipe due to negative pressure
(Link to Figure 1 photo illustrating an example of a pipe that has collapsed due to negative pressures).

Figure 2 Example of a collapsed pipe due to negative pressures
(Link to Figure 2 photo illustrating an example of a pipe that has collapsed due to negative pressures).

Literature Review

A literature review was conducted on the topics of air-water flows in pipes related to emergency gate closures. A summary of reviewed sources is shown in Appendix A. 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). For moving hydraulic jumps Parvaresh et al (2006) and Nasvi et al (2010) have conducted experiments in rectangular open channels. However, there is limited information in the literature addressing moving hydraulic jumps in closed conduits.

A hydraulic jump moving down a pipe is a natural result of an emergency gate closure. For vent sizing estimates, it is important to predict both the speed and air entrainment of a moving hydraulic jump, which became the main focus of the physical modeling efforts. The total air demand with a moving hydraulic jump is the volumetric flowrate of air passing through the vent system required to prevent negative pressures in the conduit. The total air demand includes the air entrained through a hydraulic jump as well as the change in air volume created by the movement of the jump downstream (Figure 3).

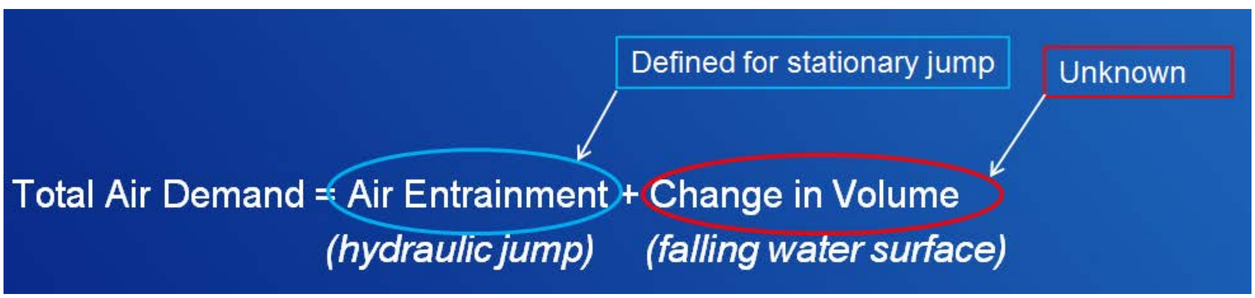


Figure 3 Equation for total air demand.

Experimental Methods

Physical Modeling

The laboratory physical model is comprised of a 12-inch diameter pipe on 0.55- and 26.0-percent slopes as illustrated in Figures 4 and 5. The arrangement consists of a slide (emergency) gate at the upstream end, which is operated with a variable speed motor, followed by a 3-inch 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 located at the downstream end of the pipe.

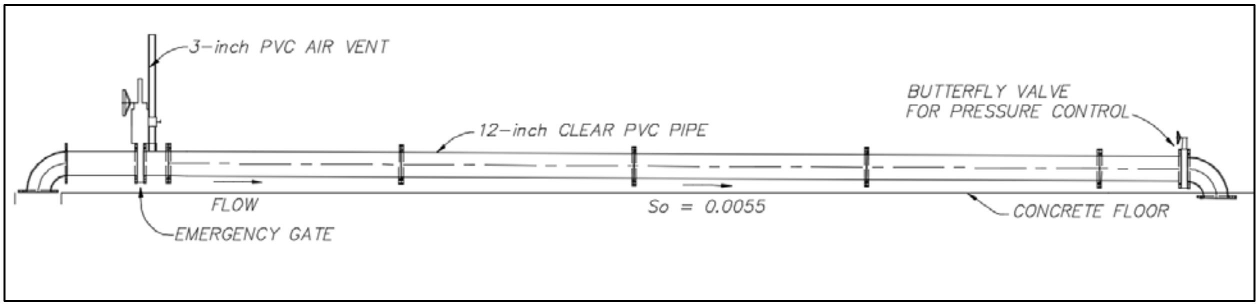


Figure 4 Profile view of 0.55-percent slope model. Flow is from left to right.

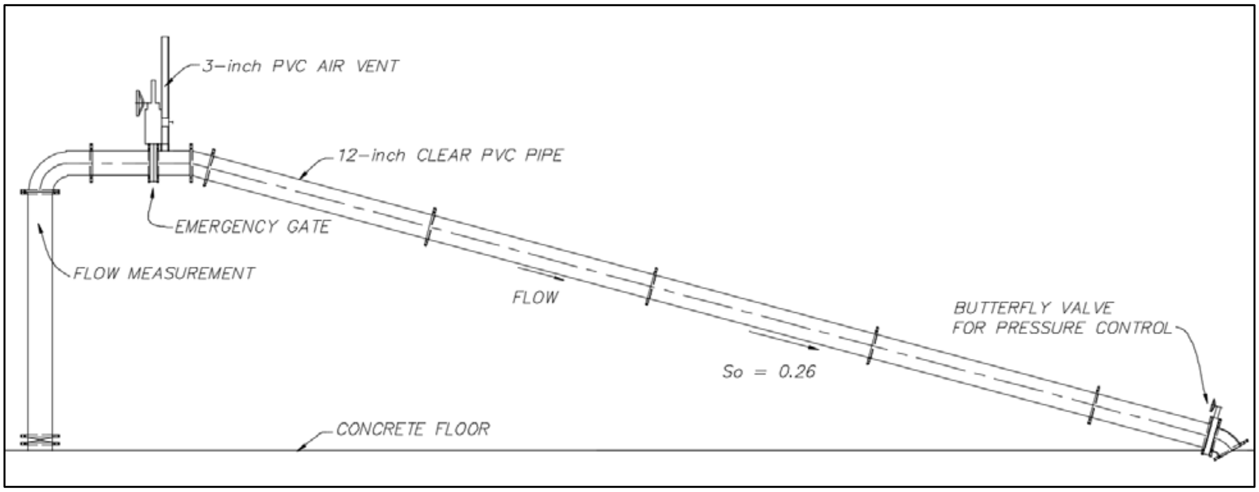


Figure 5 Profile view of 26-percent slope model. Flow is from left to right.

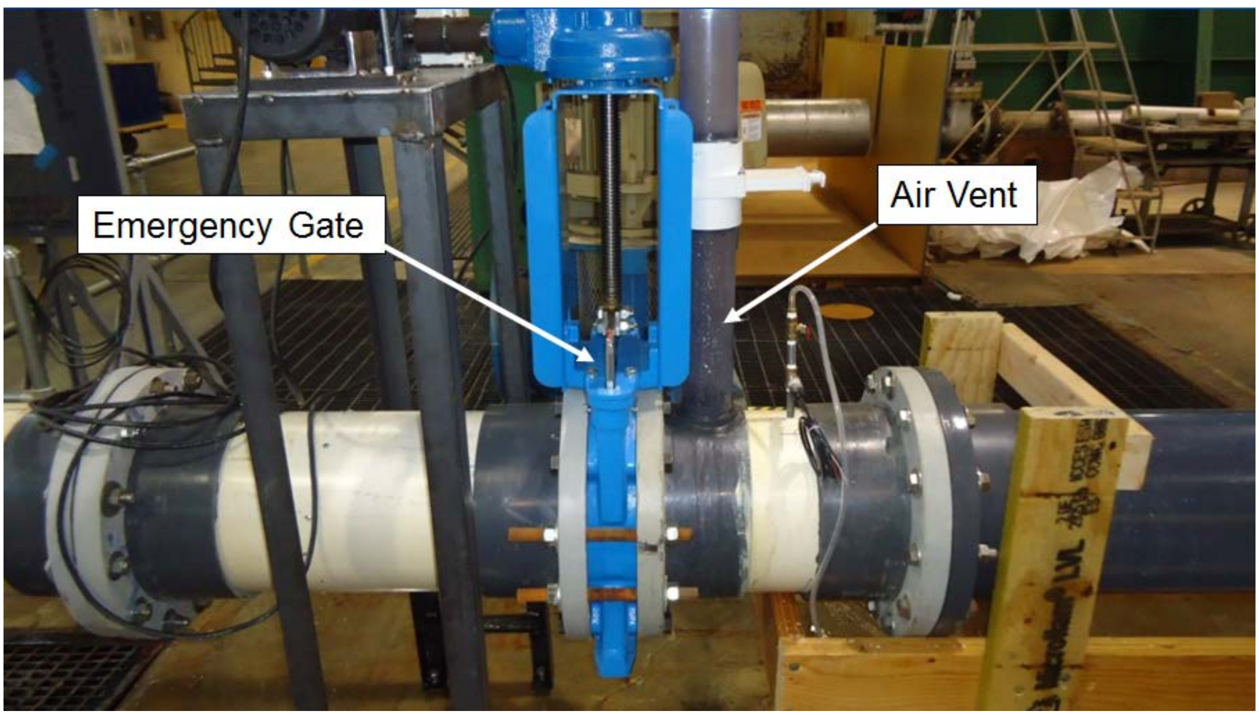


Figure 6 Emergency gate and air vent on 0.55 percent physical lab model. Flow is from left to right.

Initial water flowrates, vent sizes, and gate closure rates were varied at each pipe slope. Flowrates were controlled with the lab's pump control system. Initial laboratory tests produced maximum flowrates for the 26% slope arrangement that were limited as a result of the higher inlet elevation and increased head on the pump. The air vent size was varied by inserting a fitting with different orifice sizes (0.5, 0.75, 1.125, 1.5, and 3-inch diameter) at the top of the air vent pipe. Gate closure rates were controlled using the variable speed motor.

Test Procedure

Each test run began with a steady-state flowrate in the pipe before the emergency gate started to close. As the gate closed the air vent was manually opened to allow air flow into the pipe when the internal pressure downstream of the gate was sufficiently low to initiate venting. Attempts were made to hold the pressure upstream of the gate 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. Back pressure in the pipe was controlled by the downstream butterfly valve whose position was held constant 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. Average hydraulic jump speeds were estimated using an HD video camera (30 frames per second) and visible station markers located along the test pipe.

Numerical Modeling

Numerical modeling efforts involved restoring and updating air vent programs that have been developed in Reclamation's Hydraulics Laboratory since the 1960s. These included the "Air Demand - Falling Water Surface" program specified in Engineering Monograph No. 41 for hydropower penstocks (Falvey H. T., 1980), a program utilizing the Method of Characteristics for low-level outlet works (Frizell, 1993), and a more recent hybrid approach using method of characteristics and hydraulic jump air entrainment (Kubitschek, 2014) for application to both penstocks and low-level outlets.

Results

Physical Modeling

Approximately 100 test runs each were performed for both the 0.55 and 26.0 percent slope model configurations. The size of the air vent significantly influenced airflow and confirmed that the 3-inch vent was “oversized”. Figures 7 and 8 show an example of the internal pipe pressure and airflow for an undersized (3/4-inch) and oversized (3-inch) air vent. Verifying that the 3-inch vent was indeed oversized allowed the true total air demand to be determined without the influence of constricted air flow.

For the 0.55 percent slope observations showed that for undersized vents, the hydraulic jump speed did not always correlate with air demand. For vent sizes less than 1.125-inch jump speed increased significantly. With this condition the jump would hold at a stationary point, usually near the upstream end of the pipe, until it finally released and rapidly moved downstream. Video documentation showed that the jump started to move when air 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 negative upstream pressures due to an undersized air vent. This process is shown in the time series photos in Figure 9.

Since air flow travelled back upstream, the incoming air flow through the vent decreased and the internal pipe pressure increased temporarily during the same gate position range for which jump movement occurred in the video (Figures 7 and 8). Jump movement was often erratic and unsteady both before and after the burst of downstream movement.

This process was not observed in the 26.0 percent pipe model which produced steady jump speeds for all vent sizes even though air vent flow was reduced. Air flow and internal pipe pressure results appeared similar to the examples shown in Figures 7 and 8 when compared to gate position.

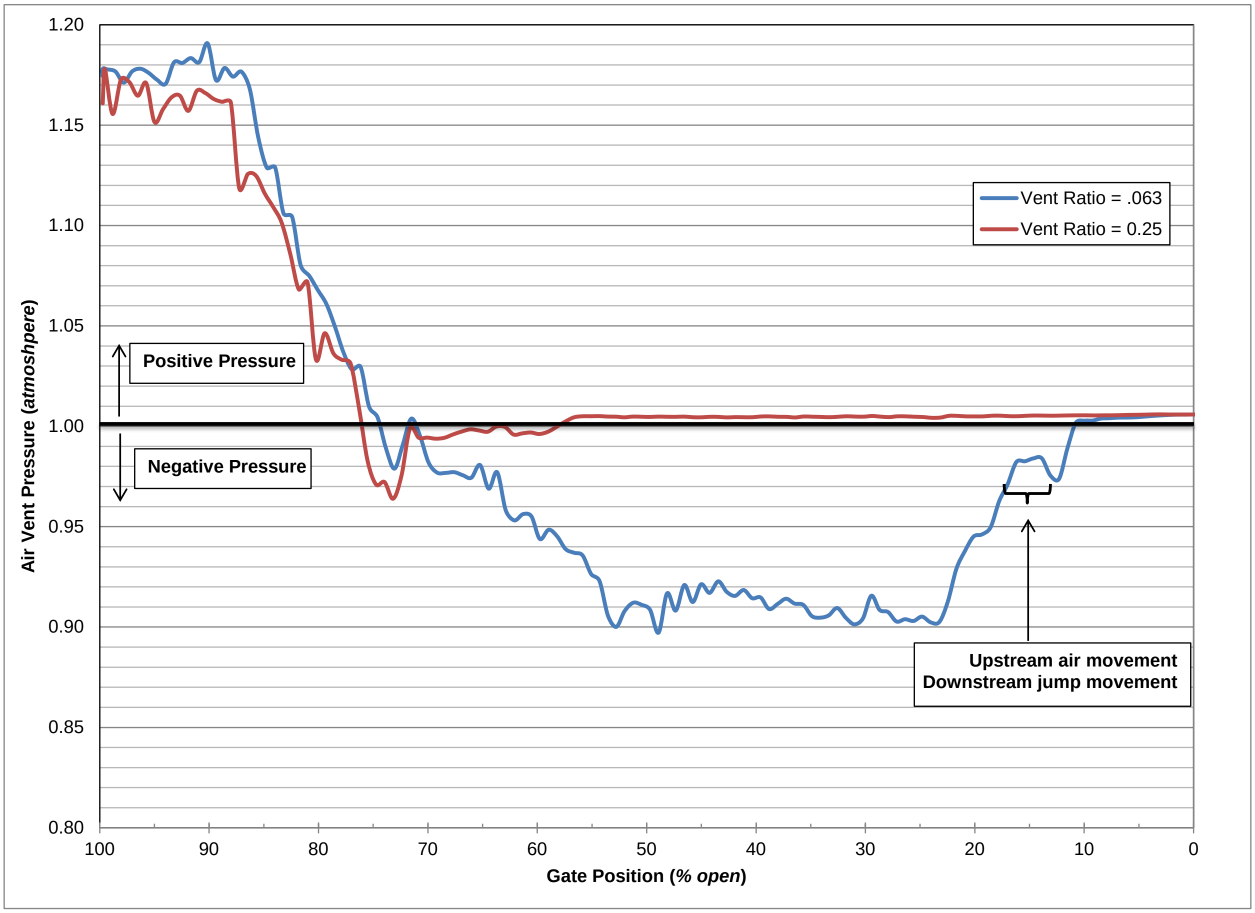


Figure 7 Comparison of internal pipe pressure vs. gate position of the 3-inch (red – vent ratio 3/12 = 0.25) and ¾-inch (blue - vent ratio 0.75/12 = 0.063) air vents. Pressure is standardized to local atmosphere indicating that pressure less than 1 atmosphere is negative.

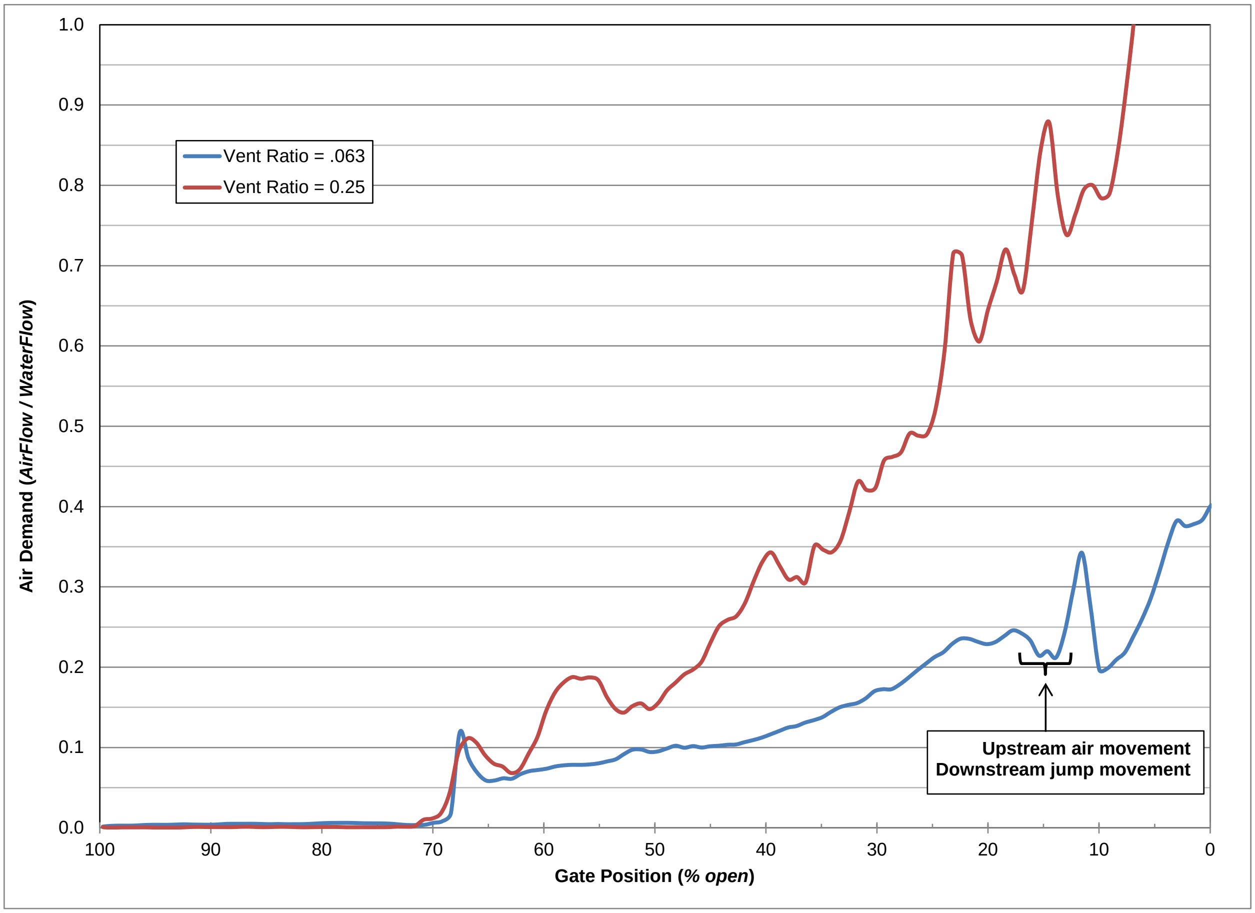
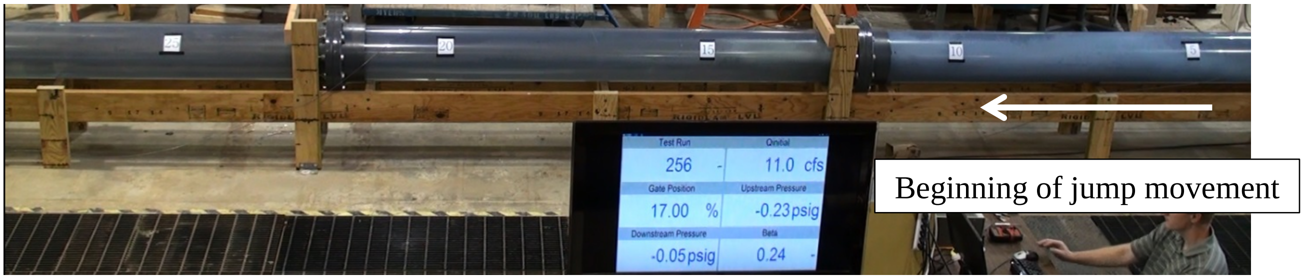
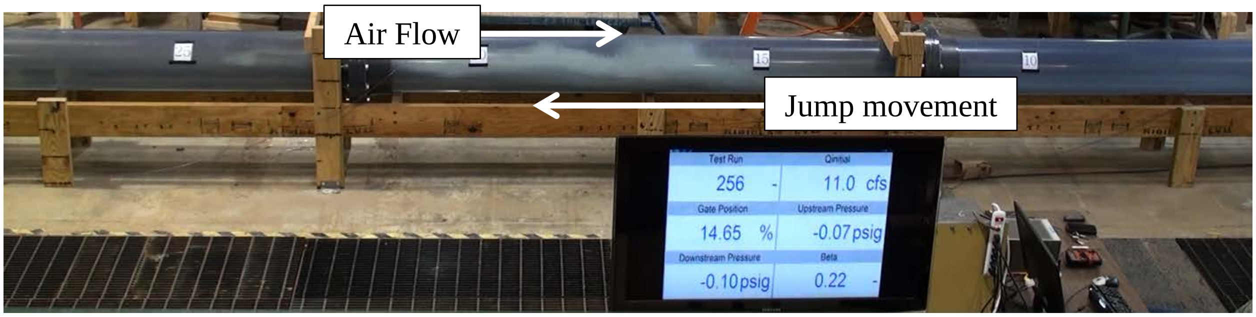


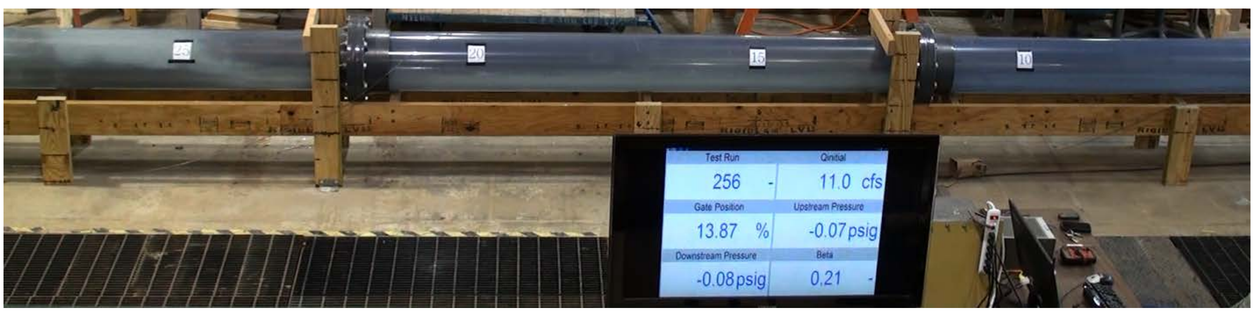
Figure 8 Comparison of Air flow/Water flow vs. Gate Position of the 3-inch (red – vent ratio 3/12 = 0.25) and ¾-inch (blue - vent ratio 0.75/12 = 0.063) air vents.



(a)



(b)



(c)

Figure 9 Time series photographs of jump motion with an undersized air vent: (a) Jump is released and begins movement (17% gate opening), (b) Jump moves downstream with air flowing back upstream (14.7% gate opening), and (c) Jump is halted again further downstream in the pipe (13.9% gate opening). Water flow and jump movement are from right to left.

The ratio of maximum air flow to water flow vs. hydraulic jump speed is shown in Figure 10 for multiple gate closure times. The trend shows that air demand increases for slower gate closures, which suggests that air entrainment due to the hydraulic jump (Kalinske & Robertson, 1943) accounts for a significant portion of the total air demand. This occurs because air entrained through the hydraulic jump is likely greater for slower jump speeds, similar to a stationary jump, and decreases as jump speed increases. Additional efforts to find a functional relationship between air entrainment and hydraulic jump speed using dimensional analysis of the existing data set would be valuable.

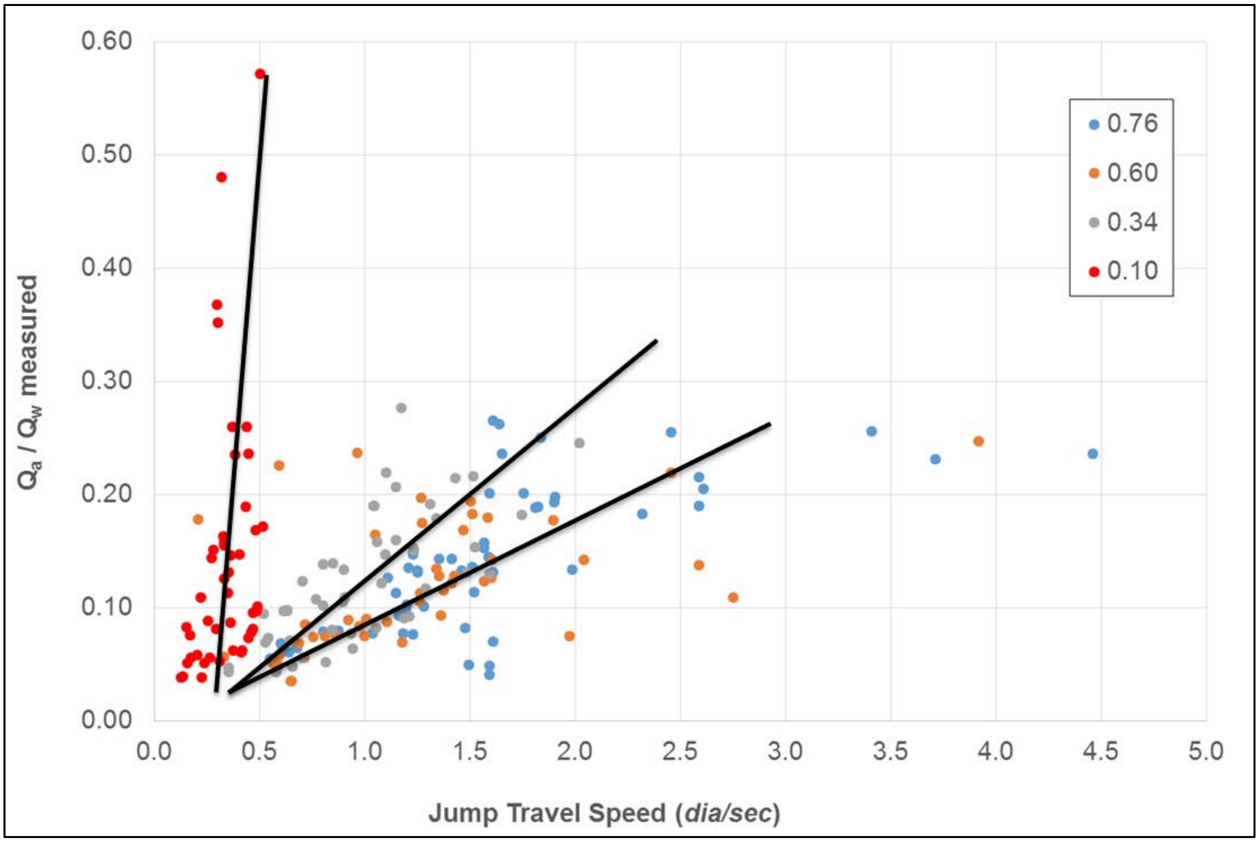


Figure 10 Ratio of maximum air flow to water flow vs. hydraulic jump speed for various gate closure rates (percent open per second).

Scatter in the data is common for experiments involving air-water flows. First of all, the mixture of air and water in hydraulic jumps is very turbulent and erratic in nature. Including multiple variables (e.g. gate closure time and air vent size, Figure 10) in the experiment may also increase data scatter. Finally, limitations in the lab facility may account for some uncertainty as it was difficult to manually control the pump pressure upstream of the gate to provide a constant reservoir head throughout each test run.

Hydraulic Jump Speed

Using dimensional analysis, hydraulic jump speed can be defined as a function of initial water discharge, pipe diameter, and gate closure time. This functional relationship in terms of non-dimensional parameters is shown in Figure 11 which represents both pipe slopes for the 3-inch vent size data to ensure that the total air demand was not restricted by air vent size. Each data point represents the average of three repeated test runs of the same condition, resulting in a coefficient of determination R^2 = 0.91. The relationship resulted in Equations 1 and 2 below to predict hydraulic jump speed based on parameters that are commonly known for application to an actual facility.

$$V_{hj} = \frac{35.465[T_r]^{-0.704} Q_i}{{D_p}^2} \qquad \text{Eq. (1)}$$

$$T_r = \frac{T_c Q_i}{{D_p}^3} \qquad \text{Eq. (2)}$$

Where:

V_{hj} = hydraulic jump speed (*ft/s*)
Q_i = steady state water discharge when gate begins to close (ft^3/s)
D_p = inside diameter of the penstock (*ft*)
T_c = time to close the gate from fully open to fully closed (*s*)

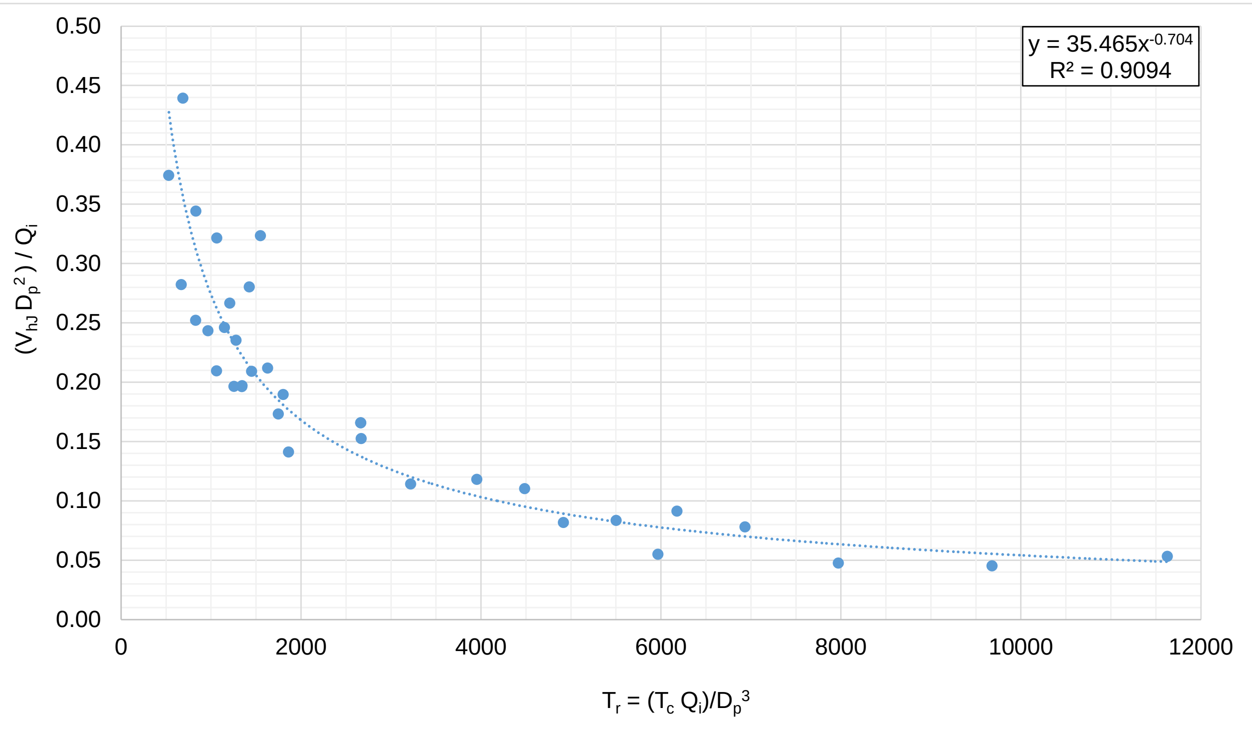


Figure 11 Plot of dimensionless parameters to predict hydraulic jump speed for an emergency gate closure.

Numerical Modeling

Falling Water Surface – Penstocks with turbines

The only available data (source code and output files) for this program were in hard copies of Engineering Monograph No. 41 and other data files archived by the Hydraulics Laboratory group. These data were scanned to pdf and recompiled electronically using text recognition and significant debugging with a modern FORTRAN compiler. After restoring the program to its original functionality, improvements were made such as removing hard coded parameters of specific test runs, setting up variable input files for more efficient use, etc. This source code is now fully functional and has been compiled for use in Windows 7 (64-bit). The program can be run with different sets of input data without recompiling the source code. Future improvements could include converting the sources code to VBA or other language for useful application.

The source code and output data from various versions of this program had to be organized and were compared to the updated version of the program. Figure 12 compares output from the updated program to a version used for air vent sizing of Morrow Point Powerplant in the mid 1960's (Falvey H. , 1968). The updated version has better agreement with a more recent version (Figure 13) that was used around 1969 and was compared to results from an emergency gate closure test at Morrow Point (Dexter, 1973) in Figure 14. Differences in results may be explained by different gate closure times used in the numerical model and field test.

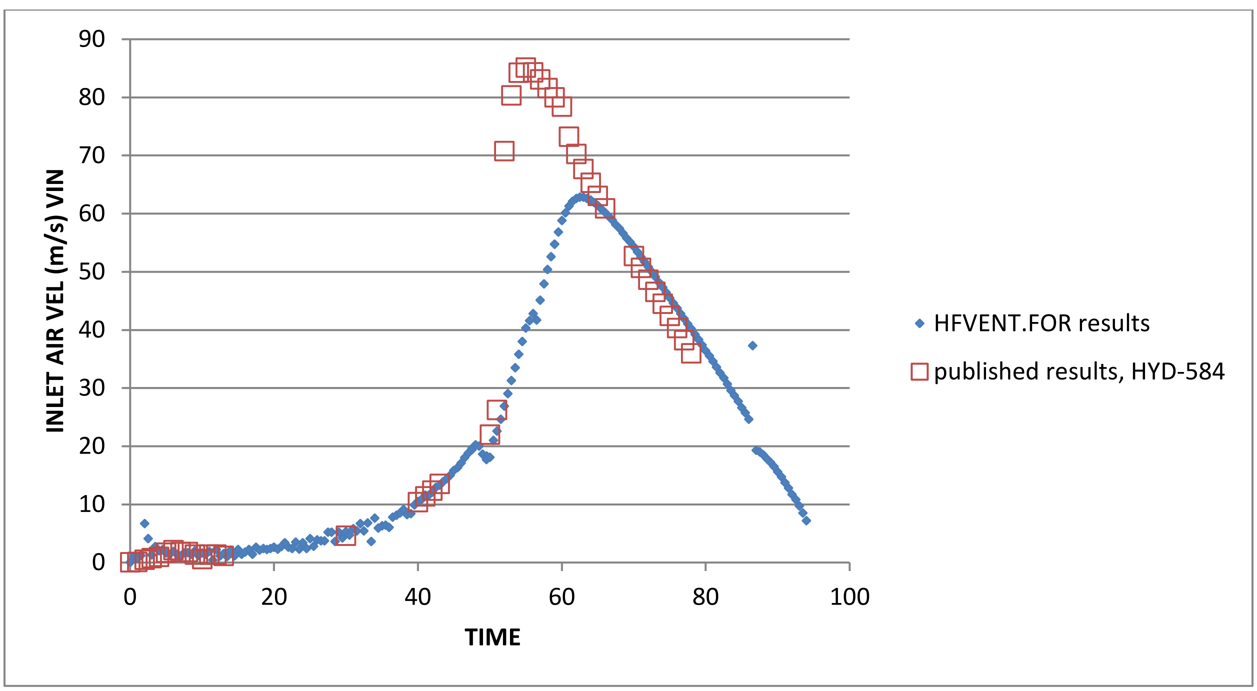


Figure 12 Comparison of current code (blue) to the version published in HYD-584 (red - about 1968). Results are of the air vent velocity for Morrow Point Dam.

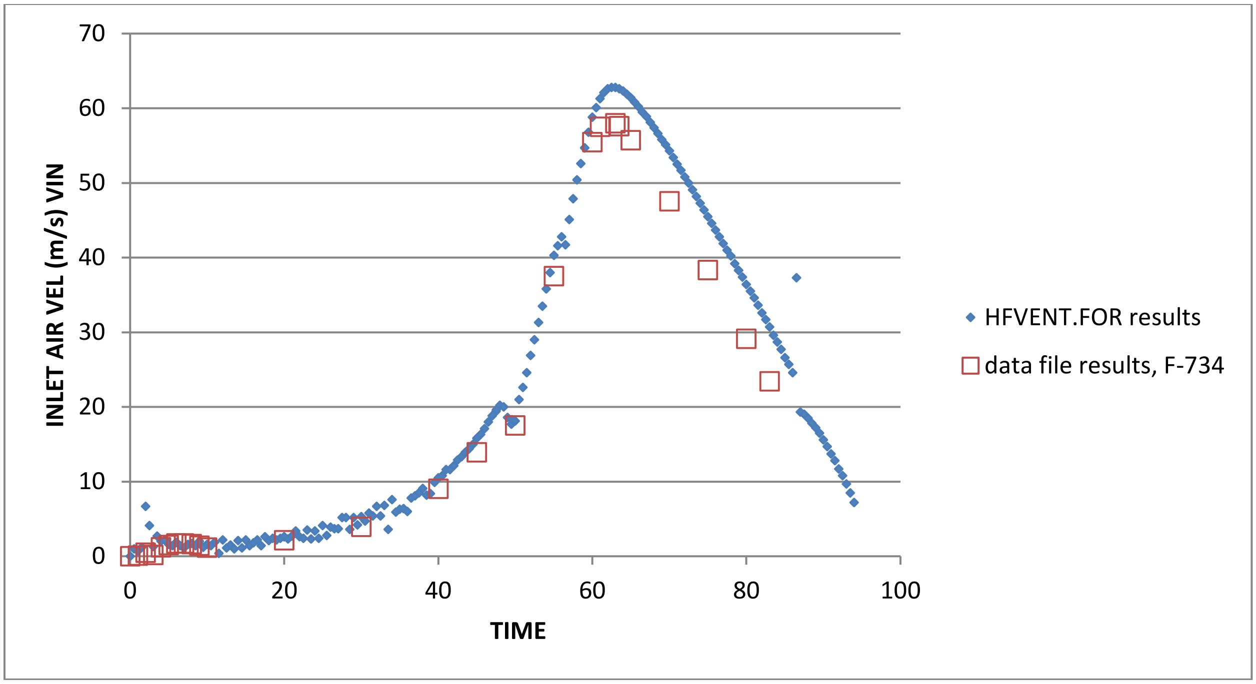


Figure 13 Comparison of current code (blue) to an updated version of the program (red - about 1969). Results are of the air vent velocity for Morrow Point Dam.

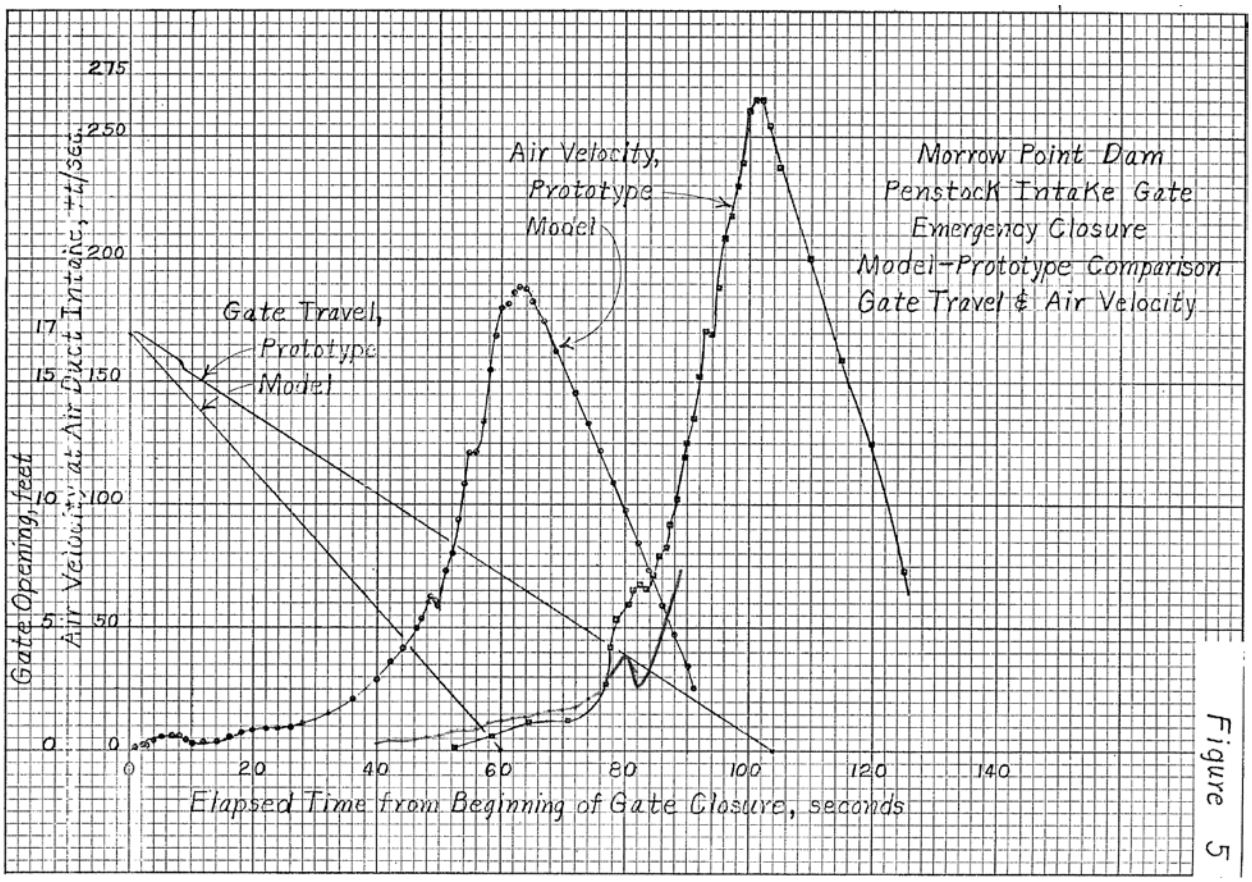


Figure 14 Comparison of the numerical program to a field test at Morrow Point (about 1973). Differences in results are due to different gate closure times used in the numerical program.

Figure 15 compares the updated program to results of a test run documented in Appendix III of Engineering Monograph No. 41. Unfortunately, only the first 40 seconds of data were saved in the monograph and no comparison can be made for the interesting part of the test run when air velocities reach their peak.

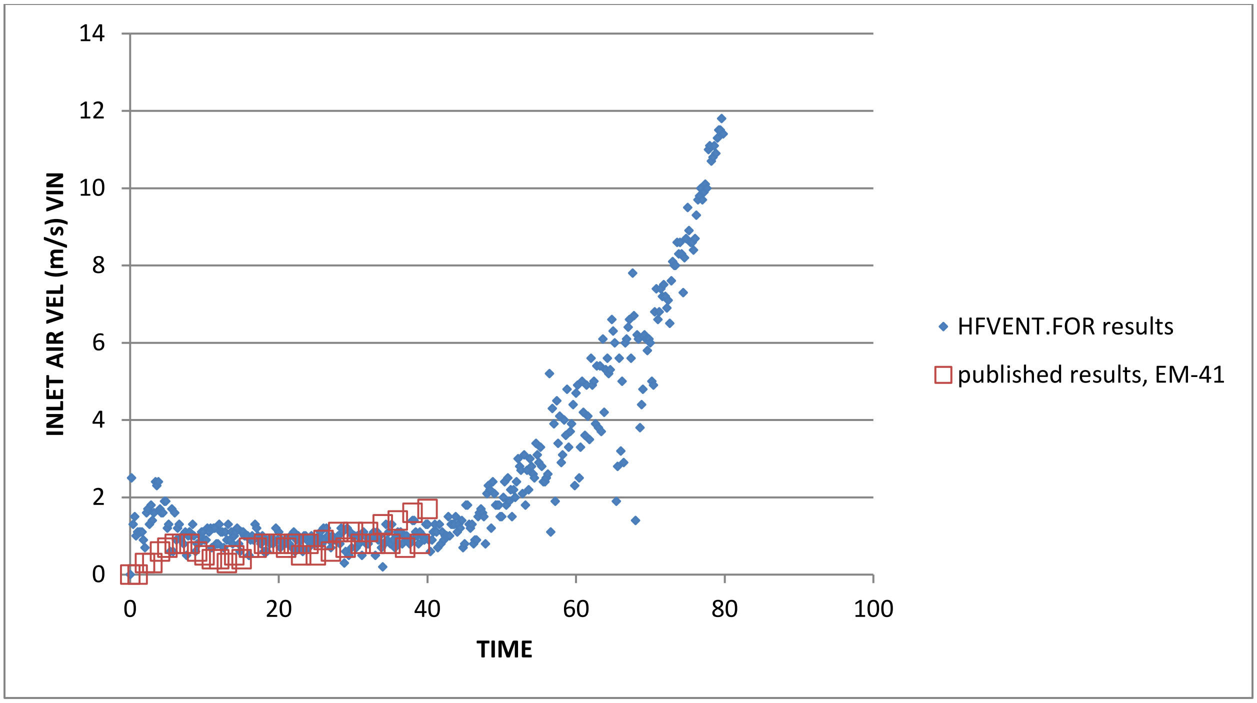


Figure 15 Comparison of the current code (blue) to version listed in the 1980 Engineering Monograph No. 41 (red).

Method of Characteristics – Low-level Outlets

This program was originally developed by Wylie and Streeter (1983) and was applied to several low-level outlets in Reclamation by Frizell (1993). It applies the Method of Characteristics to estimate pressures and flows at representative nodes within the outlet pipe. Boundary conditions include an upstream reservoir, a guard/emergency gate, an air vent/valve, and a downstream control gate. Air flow through the vent system is determined using the ideal gas law. As before, source code data for this program had to be reconstructed and debugged with a modern FORTRAN compiler. Portions of this code related to the air valve boundary condition were missing and had to be re-written. The FORTRAN code was then converted to VBA language and is now fully functional in a spreadsheet application. More detailed information about this program and its previous applications to Reclamation's facilities can be found in Frizell (1993).

The updated spreadsheet program was compared to a test run of the shallow slope physical model (Figure 16). Results compared reasonably well with very few adjustments of parameters in the numerical model. Further adjustments to the discharge coefficients of the air vent system and downstream control valve (if known) would likely improve the comparison.

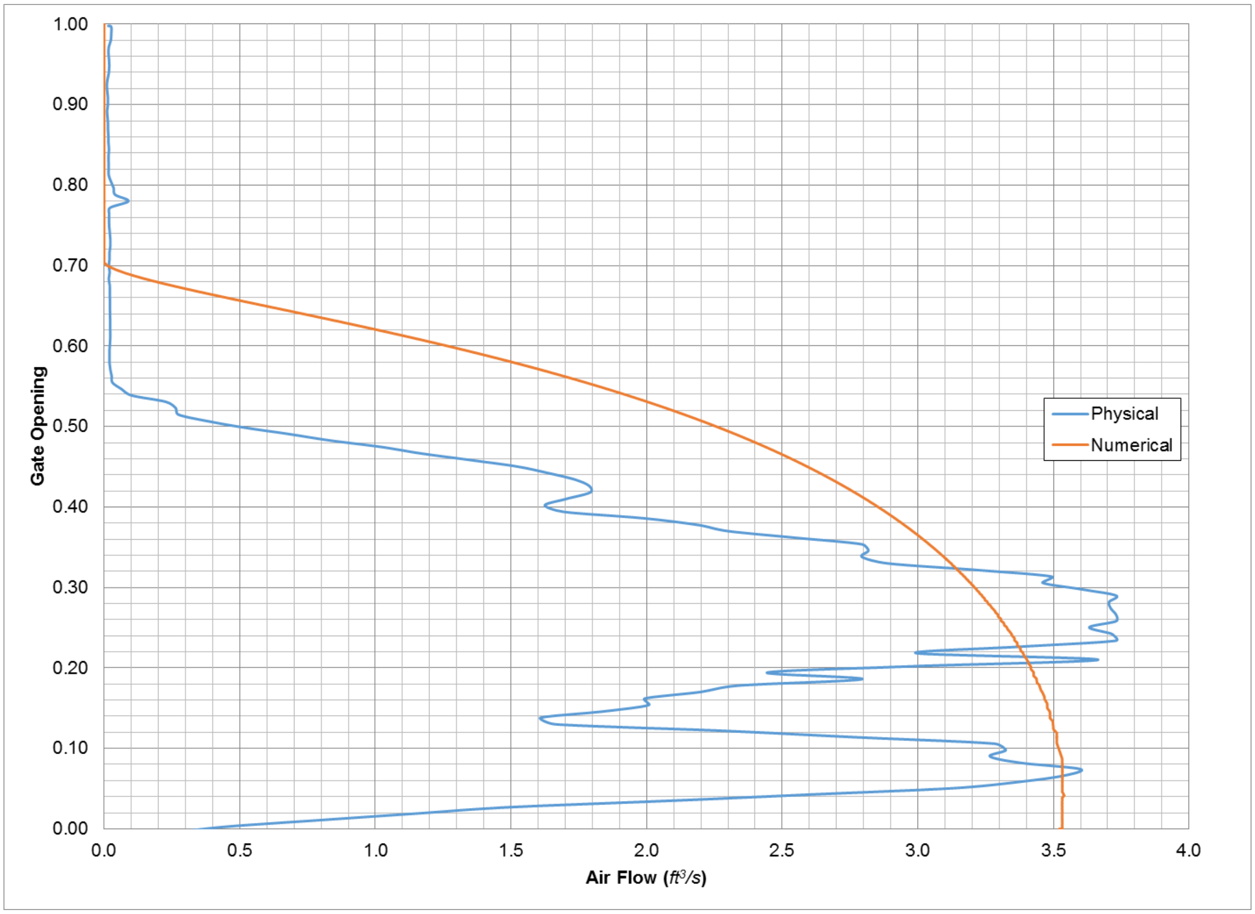


Figure 16 Comparison of total air demand results from the updated program to the 0.55% physical pipe model.

Hybrid Program

This program was developed by Kubitschek (2014) and written using Mathematica software. It uses the Method of Characterizes until the pressure downstream of the emergency gate drops sufficiently for air to flow through the vent system. At that point air flow is estimated by the change in water volume based on a flow difference between the emergency gate and downstream control valve. In addition, Froude number is determined at each time step based on the emergency gate position to estimate air entrainment (Kalinske & Robertson, 1943) and account for the total air demand. Results from recent physical model testing will help refine air entrainment predictions for moving hydraulic jumps which can be added to the code. Further development and comparisons of this program to physical model results were not completed due to scheduling and funding limitations.

Conclusions & Recommendations

The physical pipe model, which included an emergency gate and air vent, provided valuable data from dynamic emergency gate closure tests to support further development of improved methods for air vent analyses. Primary conclusions include:

- A relationship for predicting the speed of a moving hydraulic jump as a function of initial water discharge, diameter, and gate closure time was found. These parameters can be used to predict the speed of the hydraulic jump for pipe slopes up to 26 percent.
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Appendix A – Literature Review

REFERENCE	NOTES
Reclamation's Experience with Air Vent Sizing	
(Falvey H. , 1968)	Documentation of a mathematical code written in Fortran code to size air vents for penstock gate chambers. It predicts pressures downstream of an emergency gate and air vent velocities for penstock emergency gate closures. The code assumes energy and momentum equations for water flow through the emergency gate and chamber as applies an iterative change in volume over time to estimate airflow through the vent and gate chamber. The code does not assume any air entrainment from a hydraulic jump. The code in this report was applied to a penstock at Morrow Point Dam.
(Falvey H. T., 1980)	Engineering Monograph No. 41 on Air-Water flows in hydraulic structures. Discusses research findings and applications to both open-channel and closed-conduit flows. Appendix 3 includes an updated version of the Fortran code applied to Morrow Point.
(Dexter, 1973)	Reports the results of a field test of an emergency gate closure at Morrow Point Dam. Among other parameters, air vent velocity and pipe pressures were recorded and compared to predictions from the mathematical model. Absolute values of air velocity and pressure drop compared reasonably well.
(Frizell, 1993)	Documents a different mathematical code for application to low-level outlet works, which typically have shallow slopes (EM 41 code cannot apply to shallow slopes). This code utilizes the Method of Characteristics, generally applied to hydraulic transients, with boundary conditions that applies the ideal gas law to estimate airflow through a vent downstream of the emergency gate. The report compares results from the mathematical model to a physical model of Cedar Bluff dam as well as field test results from Silver Jack and Tieton dams. Results compared very well to those from the physical model but significantly overestimated airflow compared to the Silver Jack field results (like due to a clogged air vent). Field testing did not produce actual airflow results for comparison.
(Kubitschek, 2014)	Another mathematical code was written to predict pressure drop and air flow for an emergency gate closure of the Helena

REFERENCE	NOTES
	Valley Power/Pumping plant. This code utilizes the Method of Characteristics while the pressure downstream of the gate is positive. As soon as the pressure drops to atmospheric or lower, the code estimates airflow by entrainment through a hydraulic jump in the downstream pip assuming the Kalinske & Robertson equation. The code does not account for the change in volume as the hydraulic jump moves down the pipe. To date there are no field data for comparison.
Moving Hydraulic Jump	
(Aydin, 2002)	A physical model study of a penstock emergency gate closure at a hydropower plant. Compares physical model study results to a mathematical model that uses energy and continuity equations. Only maximum airflows and pressure drops are given relative to a dimensionless closure rate of the emergency gate. Generally, the mathematical model slightly under predicts the actual airflow. Their use of dimensionless terms such as the gate closure rate were useful and applicable to the current study.
(Nasvi, Asmeer, Mowsoom, & Pathirana, 2010)	Study that investigated the influence of specific energy and momentum on the movement of a hydraulic jump in a rectangular flume. Other than application of the momentum equation, physical results are not applicable to the current study due to differences in geometry and slope.
(Parvaresh Rizi, Kouchakzadeh, & Omid, 2006)	Study that investigated moving hydraulic jumps in a rectangular flume. Compared results to energy and momentum equations. Again, physical results are not applicable to the current study due to differences in geometry and slope.
Air Demand of Stationary Hydraulic Jumps in Closed-Conduits	
(Kalinske & Robertson, 1943)	Classic research paper on air entrainment through hydraulic jumps that go from open channel to closed-conduit (pressurized flow) in pipes. Developed a relationship of the air demand (airflow/waterflow) to the Froude number immediately upstream of the jump.
(Escarameia, 2007)	Study that compared hydraulic jump air demand results to previous studies. Showed differences that were likely due to

REFERENCE	NOTES
	the geometry of the conduit as well as downstream flow conditions.
(Sharma., 1976)	Compared hydraulic jump air demand data from the lab to prototype field tests. Showed that lab predictions underestimated actual field results, maybe due other forms of air entrainment other than through the hydraulic jump itself.
(Mortensen, Barfuss, & Johnson, 2011)	Compared hydraulic jump air demand data of four different pipe sizes in the lab (3, 7, 12, and 24 inch diameter). Found that air demand was not dependent on pipe size due to the downstream control in the pressurized conduit.
(Mortensen, Barfuss, & Tullis, 2012)	Compared air demand data for hydraulic jumps set at varying distances from the outlet of the pipe. Found that the air demand was very dependent on location which influenced the downstream exit condition for air escape.

Data Sets that Support the Final Report

If there are any data sets with your research, please note:

- U:\Active Files\Research\Active Projects\Air Entrainment
- Josh Mortensen, jmortensen@usbr.gov, 303-445-2156:
- DasyLab Test run files, spreadsheets, word doc report
- Keywords: Air entrainment, air demand, emergency gate closure
- Approximate total size of all files: 3.1 GB