RECLAMATION

Managing Water in the West

Hydraulic Laboratory Technical Memorandum PAP-1158

Penstock Air Vent Analysis for Green Mountain Powerplant

Emergency Gate Closure

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

December 2016

Hydraulic Laboratory Technical Memorandum PAP-xxxx

Penstock Air Vent Analysis for Green Mountain Powerplant

Emergency Gate Closure

JOSHUA MORTENSEN Digitally signed by JOSHUA MORTENSEN
Date: 2017.05.09 14:23:44 -06'00'

Prepared: Josh Mortensen, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68560

ROBERT EINHELLIG Digitally signed by ROBERT EINHELLIG
Date: 2017.02.08 12:26:04 -07'00'

Technical Approval: Robert F. Einhellig, P.E.
Manager, Hydraulic Investigations and Laboratory Services Group, 86-68560

JOSEPH KUBITSCHEK Digitally signed by JOSEPH KUBITSCHEK
Date: 2017.02.07 10:39:55 -07'00'

Peer Review: Joseph Kubitschek, PhD., P.E. Date
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68560

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

December 2016

Purpose

The purpose of this analysis is to determine the appropriate air vent size for penstock emergency shutdown procedures of the Green Mountain Dam and Powerplant. The penstocks and outlet works system, including the existing 14-inch diameter emergency air vents, are being either refurbished or replaced and an air demand analysis is warranted to ensure that the new air vent design is adequate to protect the penstocks under emergency operating conditions.

Background

Green Mountain Dam and Powerplant is located on the Blue River near Kremmling, CO and has been in operation since 1943. It includes two Francis turbine units with a total generating capacity of 26,000 kW. An 18-ft diameter tunnel feeds flow from the reservoir to two 102-inch diameter steel penstocks, one for each unit. At the upstream end, each penstock includes a hydraulically operated 102-inch ring-seal guard gate and 14-inch diameter air vent that runs from the top of the dam to the penstock immediately downstream of the gate. At the downstream end, each penstock bifurcates with an 84-inch diameter pipe going to a Francis turbine unit and a 50-inch diameter pipe going to a tube valve for outlet flow control.

Analyses

Penstock Collapse Pressure

The first step in this analysis is to determine the collapse pressure of the existing penstock. While the design wall thickness of the penstocks is 0.6875-inch, findings from an inspection in 2006 [1] determined that the existing wall thickness is currently 0.6135-inch which is assumed for this analysis. Equation 1 [2] estimates the collapse pressure assuming stiffening rings spaced every 40 ft along the penstock. Atmospheric pressure is assumed to be 10.85 psi at the gate centerline elevation of 7708 ft (standard atmospheric conditions). This approach estimates the collapse pressure (pressure differential) to be 44.1 psi.

$$Pc_{stiffener\ rings} = \frac{7.397x10^7\left(\frac{t}{d_n}\right)^{2.5}}{L_s/d_n} \tag{1}$$

where: t = penstock wall thickness (0.6135-inch)
d_n = penstock diameter (102-inch)
L_s = distance between ring stiffeners (40-ft, drawing 245-D-1205)

Alternatively, equation 2 provides a conservative approach [3] by assuming no stiffening rings on the penstock, resulting in a collapse pressure of 10.9 psi.

$$P_c = 5.02x10^7 \left(\frac{t}{d_n}\right)^3 \quad (2)$$

Assuming the penstock is in good condition, both equations show that collapse of the penstocks is not physically possible since a full vacuum would produce a pressure differential of not more than 10.85 psi. The air vent size is then predicated on preventing choked air flow through the vent ($P_{internal}$ / P_{atm} > 0.53) [2], and providing sufficient air for smooth operation of the guard gates during an unbalanced emergency closure.

Emergency Gate Closure Air Demand

The maximum volumetric flowrate of air through the vent (air demand) depends on the geometry and operating conditions of the outlet work system. According to the outlet works rating curve (drawing 245-D-406) and the Green Mountain operations supervisor, the maximum discharge for a single outlet pipe is approximately 800 ft^3/s which is the discharge assumed in this analysis. This analysis also assumes a gate closure time of 9 minutes, which was determined during unbalanced emergency tests of the ring-seal gates in 2014.

Physical Model

A physical model constructed at Reclamation’s Hydraulics laboratory in Denver, CO was used to estimate the air demand of the Green Mountain Penstocks. The model is part of an ongoing research study on air demand in penstocks and outlet works [4]. The laboratory test facility includes a guard gate, air vent, penstock, and downstream valve to simulate back pressure from a turbine or outlet valve. The model is used as a generalized method to simulate emergency gate closures for a guard gate and penstock. Green Mountain operating conditions were scaled using a Froude number similitude [5] and then tested in the lab model (Table 1).

Table 1 Froude scaled operating conditions used for lab model testing.

	Prototype	**Model**
Gate Diameter (*inch*)	102	11.75
Discharge (*ft^3/s*)	800	3.74
Gate Closure Time (*s*)	540	183

Numerical Simulation

A numerical approach was also applied to estimate maximum air demand. This approach assumes the total air demand to be the sum of air entrained by the hydraulic jump which develops downstream of the gate and the rate of volume change caused by the jump moving as the gate closes and the penstock is drained (Eq. 3).

$$Total\ Air\ Demand = [0.0066(F_1 - 1)^{1.4}(Q_i)] + [V_{hj}A_{penstock}] \tag{3}$$

Where: F_1 = Froude number of incoming flow upstream of hydraulic jump
Q_i = Initial penstock discharge at beginning of gate closure (ft^3/s)
V_{hj} = Average speed of moving hydraulic jump [4] (ft/s)
$A_{penstock}$ = Area of the penstock (ft^2)

Equation 3 is applied to simulate air demand during the gate closure once the pressure downstream of the gate drops below atmospheric pressure and air is drawn through the vent.

Results

Figure 1 compares the air demand results from the lab model and the numerical simulation during a gate closure. The peak air demands were 270 and 260 ft^3/s based on results from the physical lab model and numerical simulation respectively. The more conservative result of 270 ft^3/s is chosen for this analysis.

It should be noted that the laboratory physical model is not a true scaled model specific to the Green Mountain penstocks since gate geometry, slope, and outlet conditions are different in model and prototype. While caution should be used in interpretation and application of test results, they are used here as an order of magnitude comparison to numerical results. In this case the resultant maximum air demand from both methods were within 4% of each other which adds confidence to the analysis.

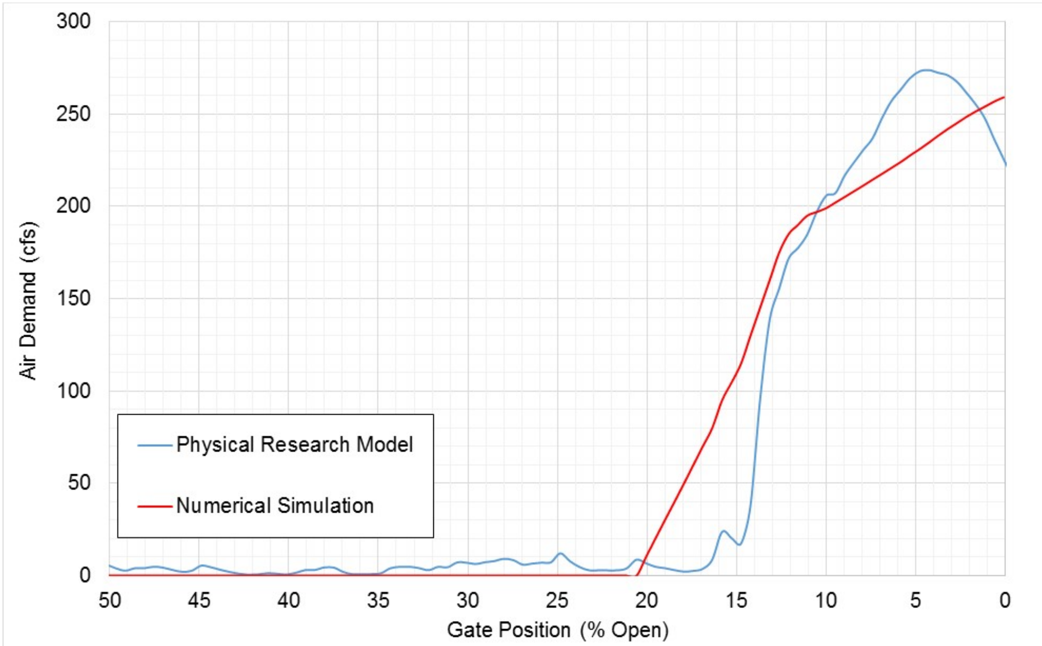

Figure 1 Comparison of air demand vs. gate position from physical research model and numerical simulation.

The minimum internal penstock pressure is calculated using equation 4 assuming an air flowrate of 270 ft^3/s and pressure losses of a 14-inch diameter air vent. This produces a pressure drop of 5.06 psi across the vent resulting in an internal penstock pressure of 5.78 psia which is adequate to prevent choked air flow in the vent (5.78 psia / 10.85 psia > 0.528). For air, 0.528 is the ratio of vent pressure to atmospheric pressure (Mach number = 1) at which flow will no longer increase with an increase in pressure differential. Based on these results, the existing air vent size (14-inch) is acceptable.

$$Q_{air} = A_{vent}\sqrt{2g\,\frac{144\frac{Patm-Pin}{\gamma}}{\sum Kl+fL/D}} \qquad (4)$$

where:

Q_a = air demand (270 ft^3/s)
A_{vent} = area of the vent (1.07 ft^2)
P_{in} = minimum allowable internal pressure (psia)
P_{atm} = atmospheric pressure @ elevation 7708 ft (10.85 psi)
$\sum K$ = sum of air vent minor loss coefficients (inlet, elbows, exit)
fL/D = friction losses in air vent (f =.015, L=346 ft, D=14-inch)

Conclusions and Recommendations

Results from this analysis show that collapse of the 102-inch penstocks is not an issue and that a 14-inch air vent pipe will adequately protect the penstocks and allow smooth gate operation during an emergency shutdown procedure. Conservative assumptions were made in the collapse pressure, air demand, and vent pressure drop predictions from this analysis.

It should be noted that air velocities exceeding 200 ft/s are possible at the entrance to the air vent near the top of the dam and safety precautions should be considered to protect project personnel and the public. One option is to restrict access to the area near the air vent inlet [2].

It is recommended that air demand data be collected during an emergency gate closure test following the completion of system upgrades. Physical data from a field test will confirm adequate operation of the new system and be useful for improving the reliability of future air demand analyses.

References

[1] Hydroelectric Research and Technical Services Group, "Penstock Inspection and Safety Assessment Program, Green Mountain Dam, Review Report," Bureau of Reclamation, Denver, CO, 2006.

[2] H. T. Falvey, Engineering Monograph No. 41, Air-Flow in Hydraulic Structures, Denver, CO: Bureau of Reclamation, 1980.

[3] American Water Works Association, M11 Steel Pipe - A Guide for Design and Installation, Fourth Edition, American Water Works Association, 2004.

[4] J. D. Mortensen and J. P. Kubitschek, "Effects of Hydraulic Jump Motion on Air Entrainment in Closed Conduits," in *6th IAHR International Symposium on Hydraulic Structures* , Portland, OR, 27-30 June, 2016.

[5] Hydraulic Laboratory Techniques, Denver, CO: U.S. Department of Interior, Bureau of Reclamation, 1980.