Design Considerations for Outlet Works Air Vents

Introduction

Outlet works air vent design is often a difficult, misunderstood, or even unknown subject for many design engineers. This article introduces the subject of air demand and air vent sizing, and discusses possible consequences of inadequate air vent design. Important design criteria and guidelines are summarized, and a conservative, generalized approach for estimating air demand and sizing air vents is provided.

Several references containing alternate design methodologies are presented in this article; however, it is cautioned that there are limitations associated with each design method. Designers should check these limitations to ensure the specifics of their projects are consistent with the methods being employed.

Why Air Vents?

An important consideration in any closed conduit design for an outlet works is the proper use of air venting. An air vent simply allows air under atmospheric pressure to flow into an outlet works conduit, introducing (or entraining) air into the flow. Specifically, a properly designed air vent serves the following purposes:

- Reduces potential for formation of low pressures within the flowing water;
- Reduces potential for unstable flow in the conduit; and
- Allows bleeding of air from a conduit prior to operation.

Air vents are typically installed downstream from a control gate or valve, where formation of low flow pressures can occur. In the absence of adequate air venting, low flow pressures can lead to cavitation, air blow back, pipe collapse, excessive vibration, and excessive noise. Each of these possible consequences is discussed below.

Consequences of Inadequate Air Vent Design

Cavitation, or the formation of vapor cavities (bubbles) in low pressure areas just downstream from the control gate/valve, is the most common consequence of inadequate air vent design. As cavitation bubbles are carried downstream from the gate into higher pressure flow areas, they rapidly collapse (implode), sending out high-pressure shock waves that can damage a conduit wall near the implosion. Cavitation damage generally occurs downstream of the gate slots in the outlet works, but can also occur on the invert downstream of the control gate. **Figure 1** shows typical cavitation damage on an outlet gate and conduit walls.

Figure 1: Typical cavitation damage on gate and conduit

Air blowback can occur as air collects on the crown of the conduit downstream of a control gate and forms a large pocket of air that can violently “blow back” toward the control gate and intake structure, causing damage to those structures.

Pipe collapse downstream from a gate can also occur if low pressure flow is extreme enough, as illustrated in **Figure 2**.

Excessive vibration in low pressure or unstable flow areas downstream of a control gate can lead to structural damage of the conduit and gate, if severe enough.

Excessive noise can occur at the air vent opening if the air vent is designed too small. The noise can even be so loud that it is damaging to hearing. At one dam, nearby residents complained of a popping noise coming from the air vent that was keeping them up at night.

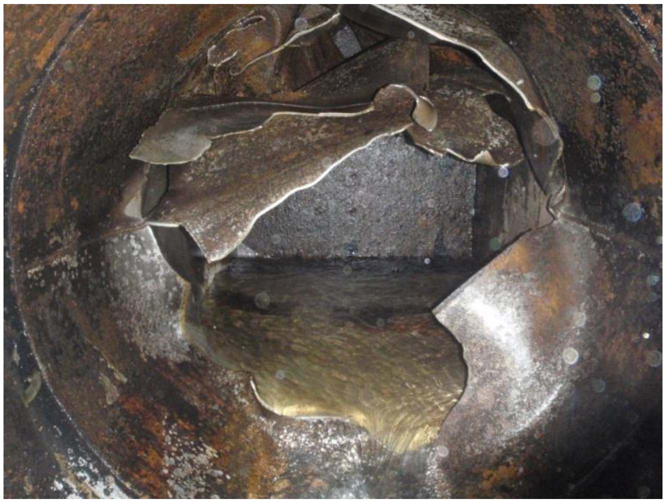

Figure 2: Outlet pipe liner collapse due to cavitation

Air Demand

Estimating air demand is the most important component of adequate air vent sizing. Air demand refers to the amount of air that the flowing water pulls into the conduit (and entrains into the flow) through the air vent and through the downstream exit portal (if not submerged).

There are a number of variables that can influence air demand, including:

- Gate opening height
- Head
- Volume flow rate and velocity of water
- Flow type (e.g., free surface flow, or hydraulic jump that closes the conduit)
- Froude Number
- Gate geometry and roughness
- Conduit length, diameter, cross section shape, and roughness
- Water surface roughness
- Outlet submergence
- Air vent geometry (e.g., entrance, bends) and head loss
- Altitude

Air demand is usually greatest at small (5 to 10 percent open) and large (between 50 to 100 percent open) gate opening heights. **Figure 3** illustrates the effect of gate openings on air demand. At small gate openings and when flow is not influenced by tailwater conditions or by a hydraulic jump, "jet flow" occurs, which entrains large quantities of air as the water jet frays or breaks up. At large gate openings and free surface flow conditions, air demand is caused by the drag force between the water surface and the overlying air column. Air demand for flow involving a hydraulic jump has been shown by studies to represent the lower bound of free surface flow air demand. When the conduit flows full, or when the gate is at the downstream end of the conduit (open to atmospheric pressure), air demand is zero.

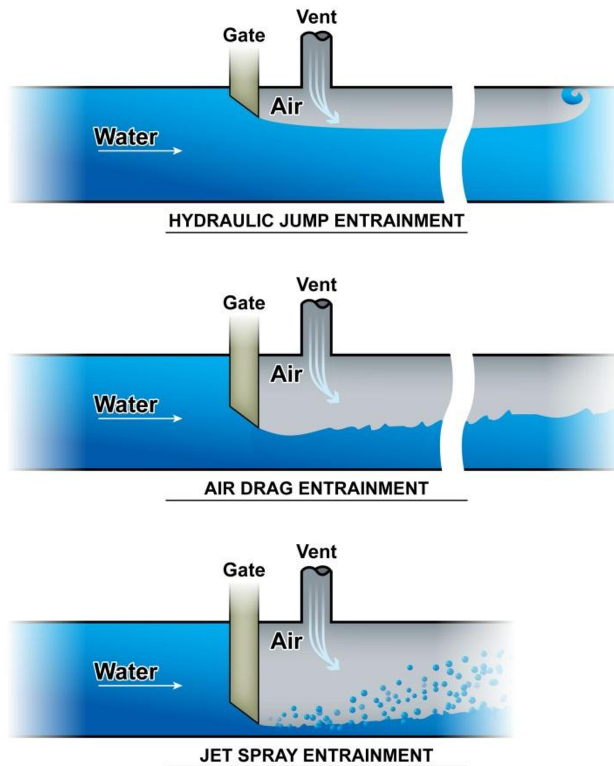

Figure 3: Gate Opening, Flow Type, and Air Entrainment

In addition to gate opening height and flow type, the other variables bulleted above influence air demand to varying degrees. Accounting for these variables in air demand estimation can be challenging for the practicing design engineer, as there is currently no known comprehensive methodology applicable to the wide range of possible outlet works configurations and hydraulic conditions represented by these variables.

Fortunately, for small to medium size dams where air vents are likely not nearly as costly as for large dams, a conservative design approach summarized below can be employed, wherein the air vent is oversized, negating the need for rigorous hydraulic analysis or model studies to account for all the variables. In cases where cost is a more significant issue, such as for low budget projects or for larger or more complex dams, a number of references describing alternate methodologies are provided below.

A Generalized, Conservative Design Approach

For flow in gated closed conduits with free surface open channel flow conditions (i.e., jet flow and air drag flow), the following equation, obtained from the 1980 publication *Air-Water Flow in Hydraulic Structures* (See references for full citation.) may be used to calculate maximum theoretical airflow rate:

$$\left(\frac{Q_a}{Q_w}\right) = \frac{A_d}{A_{wp}} - 1$$

where:

$\left(\frac{Q_a}{Q_w}\right)$ = Air Demand Ratio

Q_a = Volume Flow Rate of Air

Q_w = Volume Flow Rate of Water

A_d = Cross Sectional Area of Conduit

A_{wp} = Maximum Cross Sectional Area of Water in Conduit

Ideally, a conduit water surface profile should be calculated for a range of gate opening heights to arrive at A_{wp}. Alternatively, A_{wp} can be approximated from the water surface profile corresponding to a gate opening of 75 percent under maximum design head, as studies have shown that maximum air demand typically occurs at/near 75 percent gate opening and maximum design head. As a rough check, the design engineer should verify that the maximum volume flow rate of air is approximately equal to the maximum flow rate of water.

For cases where the water surface profile indicates that a hydraulic jump will occur, the following equation from *Air-Water Flow in Hydraulic Structures* may be used:

$$\left(\frac{Q_a}{Q_w}\right) = 0.0066(F_r - 1)^{1.4}$$

where:

F_r = Froude Number Upstream of the Hydraulic Jump *(Note: F_r is a dimensionless index of flow regime (i.e., subcritical or supercritical)).*

In a circular pipe, F_r can be calculated from the flow depth *y* by using the following equation:

$$F = \frac{V}{(gy_e)^{1/2}}$$

where:

V = Mean Flow Velocity

g = Gravitational Constant

y_e = Effective Depth = A/T

A = Cross Sectional Area of the Water in the Conduit

T = Top Width of Flow Passage = $2[y(D-y)]^{1/2}$

D = Conduit Diameter

Y = Flow Depth

After Q_a is calculated, a maximum design air velocity can be selected, and the cross sectional area and diameter of the air vent can be calculated. An example calculation using this design method is provided at the end of this article.

As a side note, the Bureau of Reclamation conservatively designs their outlet conduits so that a hydraulic jump will theoretically never occur, while the U.S. Army Corps of Engineers (USACE) allows hydraulic jumps in outlet conduits at their dams.

Alternative Design Methodologies

The 1980 USACE *Engineering Manual Hydraulic Design of Reservoir Outlet Works* (EM 1110-2-1602), together with "Hydraulic Design Criteria" 050-1 and 050-2, present a method of estimating air demand and sizing the air vent based on an envelope design curve that was developed from outlet works air demand data from 5 different dams with heads ranging from 24 to

370 feet. The method relates Froude number and air demand ratio and is generally applicable for slide and tractor gates operating in rectangular gate chambers. The envelop design curve may underestimate air demand in some cases, such as for Beltzville Dam, where actual air demand was 5 times higher than the air demand derived from the design envelop curve. This illustrates the necessity for the designer to check the limitations and applicability of a given method to ensure the specifics of their projects are consistent with the methods being employed. A spreadsheet that employs this design method is attached to this document.

The 2011 paper titled, *Determining Air Demand for Small- to Medium-Sized Embankment Dam Low-Level Outlet Works* presents a design method for estimating air demand and sizing the air vent based on laboratory-scale low-level outlet tests with an inclined gated inlet on a 3H:1V slope. The design methodology presents a series of design curves that relate gate geometry (and corresponding discharge coefficient), driving head, gate opening (10, 30, 50, 60, 70, and 90 percent), and air demand ratio. The design method uses an envelope curve of all the observed model data; with the limitation that parameters such as conduit length and air vent geometry (and associated head losses) were not considered in the model, and the method may not be applicable for gates with inclinations different than 3H:1V.

The 2008 thesis titled, *Air Demand in Free Flowing Gated Conduits* summarizes empirical design methodologies developed by previous researchers, and presents observations on significant parameters developed from a laboratory model study. The parameters studied included: Froude number, ratio of head to gate opening, surface water roughness, conduit length, and conduit slope. A possible limitation of this study is that the model air velocity measurements were not sufficiently detailed to draw conclusions.

Air Vent Design Criteria and Guidelines

The following criteria and guidelines are commonly employed in air vent design practice:

- Limit maximum air flow velocity in the air vent to approximately 100 feet/second by increasing the vent size as necessary; above this velocity an objectionable, whistling noise occurs that can be damaging to hearing.
- For safety reasons, keep children away from vent openings, and place personnel barriers around vents if the air velocity is expected to exceed approximately 50 feet/second.
- A minimum air vent diameter of 4 inches should be used for all cases to facilitate vent cleaning and maintenance.
- For valves, the air vent is typically located upstream from the point where the water jet impinges on the conduit walls.
- If the air vent is of sufficient size to interrupt rebar in the conduit wall, use a series of smaller, side-by-side air vents.
- Install an air vent through HDPE and CIPP pipe liners if there is susceptibility to internal vacuum pressures and liner collapse.
- If steel vent pipes are used and will be in contact with corrosive soils, design appropriate cathodic protection, or use a protective coating or wrap.
- A typical configuration for the end (open to atmosphere) of the air vent is to include a 90 degree elbow (see **Figure 4**) with an expanded or bell-mouth opening oriented away from the prevailing winds, with a stainless steel screen over the opening, which will help prevent debris from entering the vent, and help prevent water from entering the pipe, which could result in freezing blockage during the winter.
- Avoid air vent design features that could result in large head losses such as a small-mesh steel screen, or an excessive number of vent pipe bends.
- Take precautions against small objects (e.g., rodents, clipboards, etc.) getting sucked into the vent and creating a potential blockage; periodically inspect the air vent to ensure air is flowing freely through it and that there are no

blockages, corrosion, or structural damage that may affect performance.

- For cases where it is not possible for an air vent to have direct connection to the atmosphere, such as for control gates located in outlet works tunnels, air demand must be supplied by an air duct above the free surface of the flowing water, and the hydraulic design should ensure flow never rises to the level of the air duct.

Figure 4: Typical outlet works air vent for a small dam

It is also important to point out that there are several outlet works hydraulic flow issues that are commonly misattributed to insufficient air vent size, but are actually associated with inadequate hydraulic design or operations errors. These include surging, structural damage due to filling the pipe too rapidly, and bi-stable flow in the conduit.

References (with Links where available)

- Air-Water Flow in Hydraulic Structures, A Water Resources Technical Publication, Engineering Monograph No. 41, United States Department of the Interior, Water and Power Resources Service, by Henry T. Falvey, Engineering and Research Center, Denver, CO, December 1980.
- *Cavitation in Chutes and Spillways*, A Water Resources Technical Publication, Engineering Monograph No. 42, United States Department of the Interior, Bureau of Reclamation, by Henry T. Falvey, Research Engineer, Denver, CO, April 1990.
- *Air Demand in Free Flowing Gated Conduits*, D. Peter Oveson, A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science, Civil and Environmental Engineering, Utah State Engineering, Logan, Utah, 2008.
- *Determining Air Demand for Small- to Medium-Sized Embankment Dam Low-Level Outlet Works*, Journal of Irrigation and Drainage Engineering, American Society of Civil Engineers, B.P. Tullis, and J. Larchar, December 2011.
- Hydraulic Design of Reservoir Outlet Works, EM 1110-2-1602, U.S. Army Corps of Engineers, October 15, 1980 ; together with HDC 050-1 and HDC-050-2.

Air vent sizing example using method from the 1980 publication *Air-Water Flow in Hydraulic Structures:*

Given:

- Conduit diameter = 2 feet
- Maximum water depth in conduit corresponding to 75% gate opening = 1.5 feet
- Volume flow rate of water (Q_w) = 50 ft^3/s

Calculate:

$$A_d = \pi \frac{D^2}{4} = \pi \frac{2^2}{4} = 3.14 \text{ ft}^2$$

A_{wp} = 2.53 ft^2 *(obtained from table typically found in hydraulic textbooks that provides numerical values for area, wetted perimeter, and hydraulic radius for a partially filled circular pipe)*

$$\left(\frac{Q_a}{Q_w}\right) = \frac{A_d}{A_{wp}} - 1 = \frac{3.14}{2.53} - 1 = 0.24$$

$$Q_a = 0.24 * Q_w = 0.24*50 \text{ ft}^3/\text{s} = 12 \text{ ft}^3/\text{s}$$

Setting maximum velocity at 100 ft/s,

$$A=Q/V = (12 \text{ ft}^3/\text{s})/(100 \text{ ft/s}) = 0.12 \text{ ft}^2 = 17.3 \text{ in}^2$$

$$D_{pipe} = \sqrt{\frac{4*A}{\pi}} = \sqrt{\frac{4*17.3}{\pi}} = 4.7 \text{ inches}$$

Increase D_{pipe} to commonly available pipe size of 6 inches.