Water on Tap: Design Considerations for Outlet Controls

Introduction

Outlet works provide for the controlled release of water from reservoirs and may consist of channels, canals, or conduits. Outlet controls typically consist of gates or valves that control the rate of flow through the outlet works. The controls allow the owner/operator to regulate flow in order to accommodate downstream water needs, control reservoir pool levels or drawdown the reservoir at a controlled rate. Failure or improper operation of the outlet controls may induce failure of not only the outlet structure, but of the dam itself due to increased pressures through embankments or overtopping. Appropriate design and maintenance of outlet controls are important to ensure long-term operability and support dam safety.

There are various types of outlet control structures and each serves a different purpose. Some systems are used almost continuously, with frequent adjustment to the outlet controls, while others are seldom used and serve only as backup to another primary outlet, such as an overflow spillway for emergency or lower-level releases. This article presents an overview of the commonly used systems, the key parameters to consider in the design and maintenance of the equipment, and the hydraulic regulation those systems typically provide. Since dam operations, obligations, and impacts are specific to individual circumstances, any decisions for outlet control design or rehabilitation should include appropriate engineering analysis.

Previous *Western Dam Engineering* articles that complement this topic include: Outlet Works Air Vent Design; How Low Can You Go? The Needs and Considerations for Outlets; Letting It All Out: Hydraulic Design of Outlet Works; and Spillways on Small Dams. Structural and hydraulic analyses are an important component of outlet structure design but they are not addressed in this article.

Design Considerations

Whether a channel, canal, or conduit outlet is used, a variety of equipment and design characteristics can be considered. Among many factors that will impact the design, the most important are listed below:

- Discharge capacity
- Frequency of operation
- Access for maintenance
- Operational life
- Rate of opening
- Reliability
- Flow control accuracy
- Cost

A best estimate of these parameters must be determined to select the most appropriate solution and design for the outlet.

Power Supply for Control Systems

Frequently used outlet systems usually rely on electric motors to operate the control system. Redundant power sources are often warranted for dam safety concerns. Redundant sources can be different independent power sources, generators, or manual operation. For smaller systems, or those with low frequency of operation, manual operation may be sufficient and can be accomplished with a wheel, lever, or hand pump connected to hydraulic cylinder.

Control Operators

Gates and valves can be operated by different mechanisms, depending on the physical configuration of the system. Historically, most gates were designed with an operator consisting of a hoist with chains, vertical screws or gear mechanisms such as worm gears or linear gears. Recent designs tend to favor wire rope hoists that offer a good combination of cost, longevity, and ease of maintenance.

Photo 1: Wire Rope Hoisting Systems for Fixed Wheel Gates

Most valves are provided with an actuator that can be either rotary or linear, depending on the type of valve. There will often be a back-up manual operation with a wheel or lever. Small valves or valves with low frequency of operation may only have a manual operation system.

Hydraulic cylinders do not require large space and can be installed on top of the gates. They can also easily be submerged and connected to an accessible location such as the side of the dam. Rising concern about oil leakage is driving the use of biodegradable oil or oil free electric linear actuators for submerged applications.

Screening

Screening at the inlet is used to prevent debris from clogging, impinging, or otherwise blocking the conduit or preventing the control from closing. A trashrack of appropriate size should be designed, that can be permanently fixed or removable for cleaning. A good rule of thumb for trashrack bar spacing is half the diameter of the pipe so small debris washes through and larger debris is arrested on the rack. Motorized trashrack cleaners are typically used in areas exposed to heavy organic loading and frequent debris build up that require regular cleaning.

'Head Killer' versus Head Loss Reduction

An outlet system can serve different purposes. In the case of the outlet discharging to a channel or river, high velocity flow is usually undesirable due to its potential for channel erosion. Energy dissipation structures, such as impact basins, plunge pools, or baffles may be used to reduce the erosion potential of the discharging flows. Riprap or other armoring can also be used to protect channels from erosion.

If the flow outlet is a pressurized pipe, a cone valve or a pressure reduction valve may be used. Pressure reduction valves keep turbulence inside the piping and release flow at the desired pressure and velocity. However, when the pressure head needs to be conserved for downstream use, minimizing friction losses is desirable and can be achieved by:

- Smooth pipe entrance and smooth angles
- Low friction factor associated with gates or valves along the circuit
- Large diameter pipe to reduce velocity
- Low friction pipe lining.

Valve or Gate?

There are several considerations that affect the choice of using a gate versus a valve. Valves may be preferable for the following reasons:

- Valves tend to be chosen for smaller flows and pipes.
- Valves are easy to operate and require relatively small space for installation and operation.
- Valves can be installed anywhere along the piping system where access is easiest for operation and maintenance.
- A variety of standard valves are readily available that can be chosen to match the conditions required for flow control, pressure, and reliability.

Gates may be preferable over valves for the following reasons:

- Valves are not feasible for open channel conditions
- Gates are less expensive for control of large flows
- Access constraints may make valve operation and maintenance difficult, (e.g., on an inclined upstream face with limited access)

Location of the outlet control can be on the upstream face, downstream face or somewhere within the dam. It can also be located downstream of the dam if the water is conveyed through a pipe, in a vault, or a valve chamber. Embankment and earth filled dams tend to favor upstream control locations to avoid constant pressure conduits through the dam with the risk of leakage damaging the dam itself. Often times an upstream guard gate is accompanied by an in line control valve for redundancy and improved operation capabilities.

Types of Control: Gates

Tainter Gate: Also commonly called a segment or radial gate, these gates offer suitable control of large spillways due to their efficient structural designs that are generally less massive than other large gates. They are better suited for surface water control, although they can be used for pressurized conduits. They require relatively small motors to operate and can, in some cases, be hydraulically regulated by means of floats and counterweights, with no hoist needed. However, they are generally not cost-effective for small applications due to the level of design required.

Tainter gates usually require regular maintenance to the gate guides, lifts, and trunnion rotation anchor points to limit the risk of failure. (See the 1995 tainter gate failure on Folsom dam).

Photo 2: Tainter Gates

Fixed Wheel Gate: These gates employ a more robust system suitable for operating in smaller spaces (e.g., conduits) and in higher head conditions. They can easily be used under high pressure and are preferred for submerged applications. In cold climates, they are also chosen over tainter gates for surface applications for the good resistance they offer to ice loads and floating debris, as well as operability under high stress. Relatively large motors and hoist systems are required to overcome the weight and friction of a fixed wheel gate. The presence of wheels requires regular testing and operation to ensure proper operation. Fixed wheel gates can be installed with a stoplog system immediately upstream to facilitate maintenance.

Photo 3: Fixed Wheel Gate

Sluice Gate: Similar to fixed wheel gates, sluice gates (also called slide or knife gates) consist of a vertical plate installed through the water passage; however, the contact with the structure is a frictional interface rather than rolling wheels. Vertical contact is made by a steel or bronze plate sliding against the guide. Bronze is more expensive than steel but also more durable and reduces the friction during operation. The main advantages of sluice gates are their low cost and simplicity. Maintenance due to the wheeled system is eliminated. The induced friction restricts usage to small open areas or low head applications. A sluice gate is a good choice in situations where it is operated infrequently or for small systems. See reference [12] for more information

Photo 4: Angled Intake Sluice Gate Parallel with Upstream Face of Dam

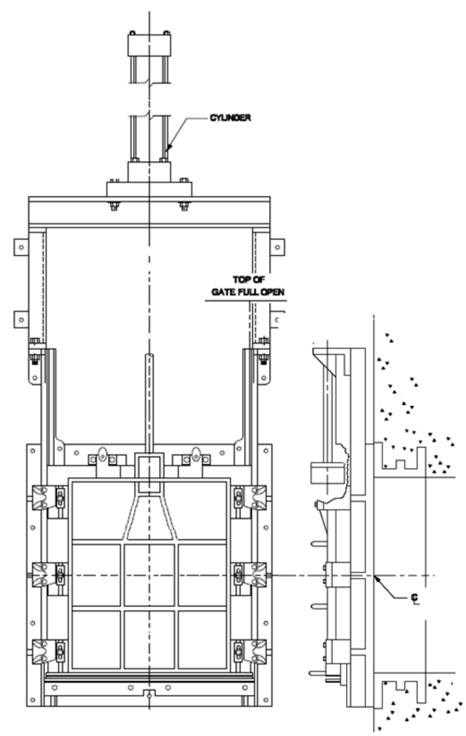

Figure 1: Vertical sluice gate, Cylinder operated

Types of Control: Valves

Valves are used to control the flow in pipes and can be located anywhere along the pipe alignment. They are particularly applicable for pressurized conduits. There are many valve options available that can be used for flow regulation and the most commonly used are described below.

Butterfly Valve: These valves were mainly used as on/off valves from their first use in the 1930s until the late 1970s, when design advancements made throttling more applicable (caution should still be used when butterfly valves are used as throttle valves). Since then, they have become the preferred system for most pipe applications because of their simplicity and reliability. Butterfly valves are used for a large range of conduit diameters and can be automatically or manually operated. They operate well for various pressure and flow conditions.

When the valve is located near another component such as a pump, turbine, bifurcation or angle, a distance of six pipe diameters upstream and four pipe diameters downstream should be maintained between components to minimize turbulence effects on the operation of the valve. Butterfly valve shafts are typically oriented vertically with the actuator on top but the following applications require horizontally mounted shafts:

- Water carrying heavy organic load or sedimentation (enhances flush effect)
- When installed downstream of a centrifugal pump or any component inducing flow rotation around the vertical axis
- When space limitations require the actuator be located on the side of the pipe

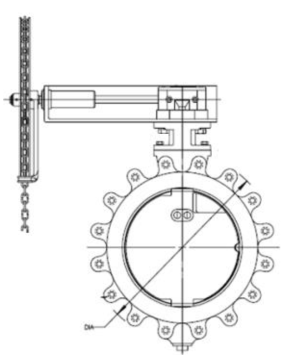

Figure 2: Butterfly Valve, with chainwheel actuator for distant operation

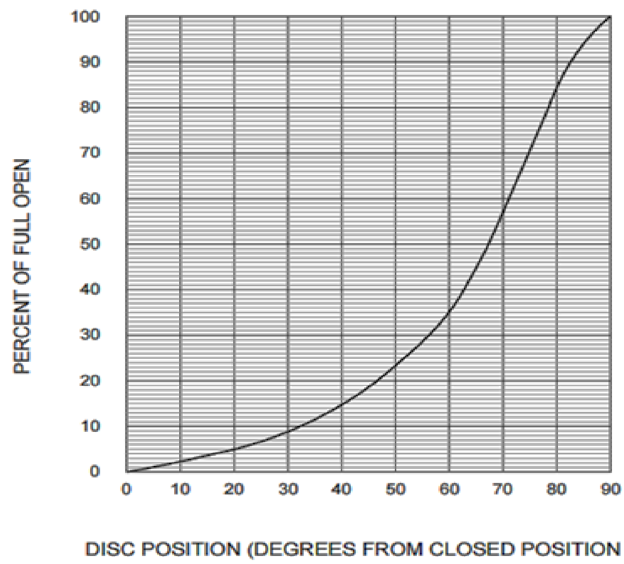

Figure 3: Typical relationship between percentage opening and disc position for a butterfly valve

Figure 3 shows that disc position versus percent opening curve is not linear for butterfly valves. For example a valve disc open at 45 degrees and would result in a nearly 20% opening. Caution should be used when using them as throttling valves.

Photo 5: Interior view of Butterfly Valve

Ball Valve: When dealing with high pressure, ball valves are usually the best choice. Ball valves minimize vibration for highly pressurized conduits and provide relatively accurate flow control. They are often used as guard valves for downstream systems such as pressure reducing valves, turbines, or piping bifurcation. Ball valves have a low friction value when fully open and they can easily be found for diameters up to 48 inches.

It is not recommended that ball valves be used for throttling as demonstrated on Figure 4 below, showing the exponential curve relating the ball position and percent valve opening.

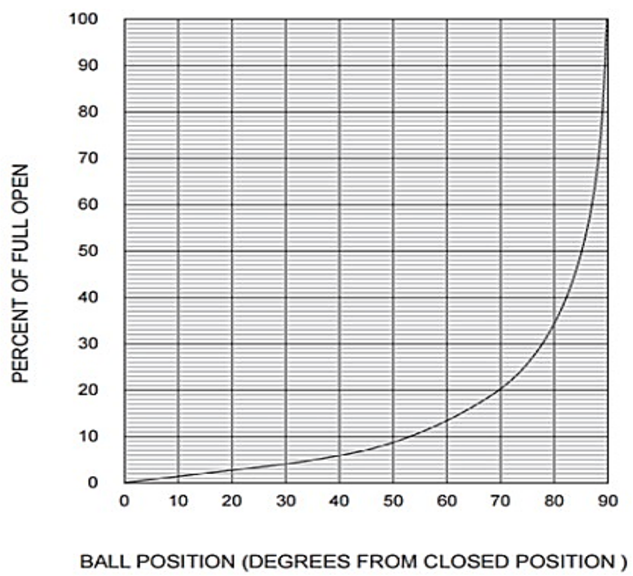

Figure 4: Typical relationship between percentage opening and ball position for a ball valve

Photo 6: Ball Valve with Actuator

Howell Bunger Valve (fixed cone or jet flow valves): These are generally used for discharge of pressurized flow from a closed conduit to free atmosphere. Fixed cone valves provide accurate control of the flow rate during discharge and their symmetric geometry minimizes the vibration associated with the release of the water. The discharge pool should be secured from the public around the jet flow area because of the danger of high pressure flow release. A hood can also be added to limit the spray area. Cold weather discharge from these valves can cause ice to form on downstream structures. This can create safety concerns if access in this area is necessary.

Photo 7: Howell Bunger Valve

In Line Gate Valve: These valves have a low friction coefficient when fully open. They are not recommended for flow regulation or throttling. Manual operation is usually slow, minimizing the risk of water hammer effect. They are sometimes divided into seating-head gates upstream and unseating-head gates downstream.

Table 1: Comparison Table for Control Valves in Pressure Conduits

	Butterfly Valve	Ball Valve	Gate Valve
External space required	Low	Low	High
Friction (open position)	High	Low	Low
Vibration during opening under high pressure	High	Average	Average
Vibration while open under high pressure	Average	Low	Low

Hydraulic Control

Valve Discharge

Valves are characterized by a coefficient, C_V, which varies with the degree of opening. This coefficient, usually given by the manufacturer, can be used to calculate the flow as follows:

$$Q = C_v \sqrt{\frac{P_1 - P_2}{S_G}}$$

With:
Q = Flow rate
C_v = Valve coefficient
S_G= Specific gravity of water
P_1= Upstream pressure
P_2= Downstream pressure

The lower the friction, the lower the C_V coefficient, and thus the higher the flow rate through the valve. If the system includes other equipment and a long pipe length driving flow at high velocity, those elements should be included in the flow rate calculations by using the Bernoulli equation.

Gate Discharge

Discharge over a gate-controlled ogee crest:

$$Q = \frac{2}{3}\sqrt{2g}\, C_d L (H_1^{3/2} - H_2^{3/2})$$

With:
Q = Flow rate (ft^3/sec)
g= Acceleration due to gravity (ft^2/sec)
C_d= Coefficient of discharge (see graph below)
L= Gate crest length (ft)
H_1= Vertical distance between sill and reservoir level (ft)
H_2= Vertical distance between bottom of gate and reservoir level (ft)

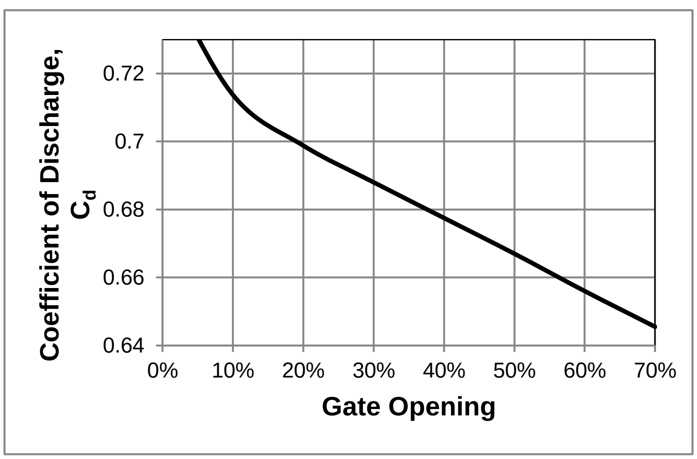

Figure 5: Coefficient of discharge for flow under gates – Reclamation, *Design of Small Dams*, 1973

See references [3] and [4]for more information

Cavitation

After fluid passes the narrowest point of the system, pressure decreases inversely as velocity increases. If the pressure drops below the vapor pressure of water at that particular condition, vapor bubbles start to form. As the fluid moves into a larger area of the vessel or downstream piping, the pressure stops dropping and increases over the vapor pressure, causing the vapor bubbles to collapse or implode. This two-step process is called cavitation and is a major factor in causing surface damage inside the pipe and valves and causing erosion on the pipe surfaces.

The cavitation index "σ", that was approved in 1995 by the Instrument Society of America, is a ratio of forces that resist cavitation to forces that promote cavitation and is written as:

$$\sigma = \frac{P_2 - P_V}{P_1 - P_2}$$

With:
σ = Cavitation index
P_1= Upstream pressure
P_2= Downstream pressure
P_V= Liquid vapor pressure

The cavitation potential is inversely proportional to the cavitation index; the lower the cavitation index, the higher the cavitation potential. It is typically recommended to keep σ above 2.5 to eliminate potential for cavitation.

The following adaptations can reduce or suppress the risk of cavitation:

- Venting (See references [2], and [8] and our previous article, Design Considerations for Outlet Works Air Vents (Vol. 1 Issue 2) for more information.)
- Use of additional valves to reduce the pressure differential
- Use of a bypass system.

See reference [7] for more information.

Water Hammer Effect

Water hammer is generated when the flow is suddenly stopped in the hydraulic conduit, and a large shock wave is generated. This situation can be produced by a sudden turbine or pump shutoff or a valve slamming shut. Pressure induced by the water hammer effect can be calculated from the Joukowsky equation:

$$\Delta P = \rho a_0 \Delta v$$

With:
ΔP= Magnitude of the pressure wave
ρ= Density of the water
a_0= Speed of sound in water
Δv= Change in the fluid's velocity

High pressure is induced into the system, creating noise and vibrations. It can result in severe damage to valves, gaskets, and any equipment exposed to water hammer.

Systems involving a long length of pipe with high pressure are more exposed to water hammer effects.
The valve must close slowly to minimize water hammer, and the safe closure rate can be calculated. If the fluid is assumed to be incompressible and the water column deceleration after closure is assumed constant, the resultant pressure can be calculated as follows:

$$P = \rho v . \frac{L}{t}$$

With:
P = Pressure (lb/ft^2)
ρ = Fluid density (lb/ft^3)
L = Pipe length (ft)
v = Fluid velocity (ft/sec)
t = Valve closure time (sec)

To mitigate the pressure induced by the shock wave in the system, a surge tank can be added. Surge tanks will act as a "bumper" to provide a release for overpressure and level the overall pressure in the pipe.

Summary

Outlet control is a critical component of dam operation. Important parameters need to be considered during the design of the outlet, such as the flow, pressure, and frequency of use. Also, the type of power source and system will be influential in choosing the appropriate equipment.

A variety of valves or gates can be used for outlet controls, each with particular characteristics. Although valves can accommodate any conduit size, they are used most often for conduits under 36 inches in diameter, with the butterfly valve suitable for most applications. The ball valve is recommended for high pressure applications and the Howell Bunger valve is used for discharge into free atmosphere.

Gates are more suitable to control outlet conduits difficult to access, and any open channel outlet or spillway application. Tainter gates involve more specialized design, but are lightweight and widely used for surface water control applications. Fixed wheel gates are more robust and heavier; they can resist high pressure and rough conditions. Finally, sluice gates are also pressure resistant and very simple, but have high friction forces, requiring more power to operate. Sluice gates are typically used on low to medium flow rate outlets with low frequency of operation.

Flow rate can be calculated with variable accuracy depending on the equipment used. Flow through valves or gates can easily be calculated using the associated coefficient. However, more complex outlet systems with several controls and long piping will require more developed calculations based on the Bernoulli equation. Gates and valves are specialized equipment that can have long lead times. Manufacturers should be consulted early in the design process.

Useful References

[1] Federal Emergency Management Agency (2005). Technical Manual: *Conduits through Embankment Dams*.
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