Spillways on Small Dams

Introduction

The purpose of a spillway is to safely convey reservoir inflows over and/or around a dam to the natural drainage channel, up to and including the Inflow Design Flood (IDF), thus protecting the dam embankment from failure due to overtopping. The IDF varies according to jurisdiction and dam hazard classification. In addition to providing sufficient flood capacity, the spillway must be hydraulically and structurally adequate and must be located so that spillway discharges do not erode or undermine the dam. Flow over spillways is a designed event and are usually not a cause for alarm on an appropriately designed and constructed dam and spillway.

Different states in the US categorize spillways differently. For example in Colorado, the State Engineer's Office (SEO) document titled *Rules and Regulations for Dam Safety and Dam Construction* defines an auxiliary spillway, as defined by US Bureau of Reclamation (Reclamation), as an emergency spillway. It is therefore recommended that the reader consult relevant state guidelines/legislation to understand the terminology used in each state. *Design of Small Dams* (Reclamation 1987) categorizes spillways as service, auxiliary, and emergency. These are described below.

Service Spillway: A service spillway is the overflow structure designed to limit or control the operating level of a reservoir, and the first spillway to be activated. Service spillways are designed to pass part of the IDF unless the service spillway is unavailable at the time of flooding due to damage, blockage, or inoperability. Service spillways are designed to pass floods that occur frequently and damage to a spillway from the passage of these floods would not normally be tolerated. Service spillways rarely appear on small water supply dams, but frequently appear on flood control dams.

Auxiliary Spillway: An auxiliary spillway is used in conjunction with a service spillway, if present, to pass the IDF. Auxiliary spillways are designed to operate for floods in excess of the flood flow used for the design of service spillways or, if a service spillway were not present, all inflows that are not stored or released through the outlet works. If used in combination with a service spillway, an auxiliary spillway may not need to be designed for the same degree of safety required for other structures and some flood damage may be considered tolerable for more infrequent flood events. In some cases, this may offer considerable construction cost savings. Spillway damage that would affect the ability of the reservoir to retain water or would threaten the integrity of the dam would not be tolerable. Flood damage to an auxiliary spillway and the associated repair and maintenance costs need to be considered during the design process. Auxiliary spillways are a common form of spillway on small dams and are the main focus of this article.

Emergency Spillway: Emergency spillways are provided for additional safety should emergencies not contemplated by normal design assumptions arise. Such emergencies may include damage to, or issues with, the service and/or auxiliary spillway or damage/malfunction of spillway gates. Under normal reservoir operation, emergency spillways are never required to function and the crest level is set above the maximum reservoir water surface resulting from the IDF. Emergency spillways rarely appear on small dams, particularly small dams with a passive (ungated) auxiliary spillway.

The design of a spillway that is both functional in terms of design, and economical from a construction cost standpoint, requires careful consideration of the associated topography, the geology, the spillway type, maintenance and operational requirements, the IDF, the dam type and the proximity of the dam to the spillway. To select an optimized and economical spillway and dam configuration, construction cost estimates are typically developed for various combinations of spillway capacities, spillway types, and dam heights.

If possible, a spillway should be located independently of the dam itself, on the left or right dam abutment, or in a saddle or depression along the reservoir rim. The locations considered should lead to a natural waterway or a gently sloping abutment where an excavated channel can be constructed beyond the dam to avoid the possibility of damage to the dam or other structures.

A spillway generally consists of various combinations of crest control structure, conveyance element (or chute), terminal structure, and downstream channel. As most small dams are embankment dams, only spillways typically associated with embankment dams are discussed in this article. Therefore, spillways typically associated with concrete dams, such as free overfall drop spillways or overtopping spillways, are not discussed. The following sections provide examples of various crest control, conveyance, and terminal structures for embankment dam spillways.

Crest Control Structures

A major component of a spillway is the crest control structure that regulates outflows from the dam. A crest control structure can be categorized as either a controlled (gated) or uncontrolled (ungated) crest structure. Most crest structures on small dams are uncontrolled for simplicity, economical construction cost, and ease of maintenance and operation. As the focus of the *Western Dam Engineering Technical Note* is predominately on small dams, uncontrolled crest structures are discussed herein.

There are six common types of uncontrolled crest structures and these are described in the following subsections of this article. For a crest control structure to realize its theoretical discharge, the hydraulic conditions both upstream and downstream must be acceptable. The approach conditions upstream should not choke the flow to the crest and the downstream conveyance element should not cause excessive submergence of the crest. In some cases, sub-optimal downstream hydraulic conditions are acceptable to achieve efficiencies in design and construction cost.

Ogee Crests

An ogee crest has a control weir that is curved in profile and is designed to closely profile that of the lower nappe of a ventilated sheet (of water) falling from a sharp crested weir. An ogee crest can also be designed so that negative pressures on the crest are within an acceptable range and the potential for cavitation is minimized. A correctly designed ogee crest control structure has high discharge efficiency and is used on most spillway control crests for large dams and commonly on small dams. An example of an ogee crest control structure is shown on Figure 1 and Figure 2.

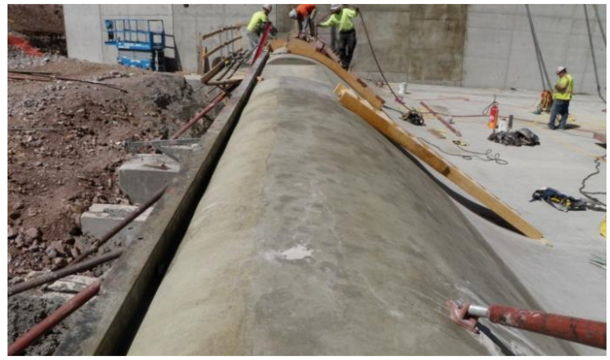

Figure 1: Ogee Crest

Figure 2: Ogee Crest

Broad Crested Weir and Concrete Sill Crests

The crest structures on many small dams, especially where space permits and where minimal discharge capacity is required, may be simple concrete sills or broad crested weir control structures. Occasionally, broad crested weirs will have a slightly rounded upstream edge to provide a more efficient inlet flow transition. Where concrete broad crested weirs are not located significantly above the channel bed to develop hydraulic control, these weirs are referred to as 'sills'. Examples of a broad crested weir and a concrete crest sill are shown on Figures 3 and 4, respectively.

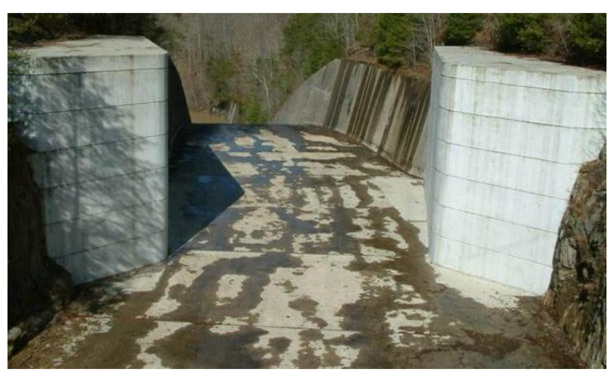

Figure 3: Broad Crested Weir

Figure 4: Concrete Control Sill

Sharp Crested Weirs

A sharp crested weir is typically formed through the construction of a thin wall and placed normal to the flow in a spillway chute. The flow depth is generally two or more times greater than the wall thickness. Sharp crested weirs often have air vents on the underside of the flow so that atmospheric pressure exists on the underside of the nappe. Sharp crested weirs are seldom used on spillways for dams and are more common in canals and flood control channels. An example of a sharp crested weir is shown on Figure 5.

Figure 5: Sharp Crested Weir

Labyrinth Weirs

Labyrinth weirs provide additional crest length across the width of a spillway to increase discharge flows, particularly at low heads. The additional crest length is obtained by utilizing a series of trapezoidal walls that provide ’cycles’ on the crest. The walls are typically thin walls that are supported on a concrete slab or other acceptable foundation. Flow patterns on a labyrinth spillway are complex. When the maximum design head for a given labyrinth weir configuration is exceeded, the discharge coefficient can decrease due to interference from adjacent labyrinth cycle(s) which can partially, or fully, submerge the weir crest. At high design heads the labyrinth discharge can begin to approach that of a broad crested weir. As with all crest structures, a labyrinth weir is sensitive to tailwater levels and when the crest becomes submerged the discharge coefficient can decrease significantly. A piano key weir offers similar discharge efficiency to a labyrinth weir, and in some cases greater discharge efficiency than a labyrinth weir. Piano key weirs are rarely constructed on small embankment dams and, therefore, are not discussed herein. An example of a labyrinth weir control structure is shown on Figure 6.

Fusegates® are most often designed with a labyrinth crest shape for more efficient discharge and to minimize the number of Fusegates® required to pass the IDF. Fusegates® are a more common installation on large dams and, therefore, are discussed no further in this article.

Figure 6: Labyrinth Weir

Drop Inlet/Morning Glory Crests

A drop inlet crest is one in which the flow enters the spillway over a horizontal lip, drops through a vertical or sloping shaft, and then flows through a horizontal or near horizontal conduit or tunnel to the downstream river channel. Drop inlets are commonly used for principal spillways and less frequently for auxiliary spillways. The drop inlet is normally located within the reservoir so flow can enter from the entire perimeter or from one or multiple sides of the crest. The profile of a drop inlet crest can be square or round, and in some cases, can have an ogee crest-shaped lip to efficiently discharge flows. On large spillways, it is common to construct guide vanes or piers at the crest to prevent the formation of flow vortices which can lead to sub-optimal hydraulic conditions and reduce discharge. Discharge control can shift from crest to the throat, or to the conveyance tunnel for these types of spillways. Where the inlet is funnel-shaped, it is often called a "morning glory" type crest structure. Morning glory crest structures (Figure 7) are more prevalent on large dams. A more common drop inlet for smaller dams is shown on Figure 8.

Figure 7: Morning Glory

Figure 8: Drop Inlet

Side Channel Crests

Typically a side channel spillway has a control crest located parallel to, and along one side, of the spillway chute. In this case, flow enters from the crest and then turns 90-degrees into the spillway chute. In some cases, a control crest is also located at the upstream end of the spillway chute to provide additional discharge. The side channel spillway crest can be configured with most of the above-mentioned crest types. Due to its unique shape with a long crest and narrow chute, a side channel spillway can often be well-suited to a narrow and/or steep dam abutment. Where suitable, a bathtub crest structure can also be considered if a crest is located on both sides and the upstream end of the chute. Weir capacity and channel capacity must be balanced in the design of these spillways to consider the submergence effects on the weir crest. An example of a side channel spillway is shown on Figure 9. A bathtub crest structure is shown on Figure 10.

Figure 9: Side Channel Spillway

Figure 10: Bathtub Crest Structure (Reclamation 1987)

Conveyance Systems

Conveyance systems are typically chutes or channels that convey flow from the spillway crest structure to the terminal structure. Conduits and tunnels are also used for conveyance systems but are less common. Chute conveyance systems are described in the following subsections of this article.

Spillway Chutes or Channels

An open channel that conveys flows directly from the crest into a stilling basin or downstream channel is referred to as a chute conveyance system. Spillway chutes are commonly located along one of the dam abutments or through a saddle some distance from the dam. A spillway chute is the most common conveyance system, particularly on small dams.

Spillway chutes typically have a prismatic cross section. The most common concrete chute design is a rectangular channel; however, trapezoidal channels are also common. Chutes can be converging or diverging from the crest structure to the terminal structure. Chutes can be lined with concrete, riprap, Reno mattresses, articulated concrete blocks, etc., or be unlined where acceptable foundation conditions exist to resist unwanted erosion during operation. In some instances, a chute can be partially unlined and lined where only certain areas of the foundation need to be protected.

The spillway chute can be smooth, rough, stepped, or baffled. Stepped and baffled chutes can help dissipate the energy of flood flows and can reduce the size of the terminal structure or in certain circumstances negate the need for a terminal structure. Spillway chutes can be designed with a constant slope or with vertical curves and variable slopes to match the dam configuration, site constraints, and/or topography. Typically, and preferably, spillway chutes are straight, but in some cases, have horizontal bends where complex flow conditions can occur and must be considered as part of the design process.

Examples of a lined spillway chute are shown on Figures 11 and 12. An example of an unlined spillway chute is shown on Figure 13.

Figure 11: Lined Spillway Chute (Concrete)

Figure 12: Lined Spillway Chute (Articulated Concrete Blocks and Riprap)

Figure 13: Unlined Spillway Chute

Conduits or Tunnel Outlets

Conduits and tunnels are used to convey spillway flows around or through a dam. These types of conveyance structures are typically used with a drop inlet spillway crest, although some overflow crests and side channel crests discharge into conduits.

Conduits typically have a vertical or near vertical shaft section directly below the inlet and then a nearly horizontal section of conduit or tunnel through or around the dam to the outlet. Most conduits or tunnels are designed to flow partially full, although many drop inlets have a shorter section of the conduit that will remain pressurized at the control point. Proper aeration is critical for conduits to operate smoothly and avoid cavitation, burping, and surging.

Conduit or tunnel linings are typically cast-in-place concrete. Some conduits consist of steel pipe that may have a cast-in-place concrete encasement to resist external pressure.

Terminal Structures

Terminal structures are required where energy from the spillway flow must be dissipated before being discharged to the downstream channel. In some cases, such as where the downstream channel is not erodible, a terminal structure may not be necessary. The more common types of terminal structures provided at small dams are described in the following subsections of this article.

Hydraulic Jump Stilling Basins

The most common type of stilling basin is the hydraulic jump stilling basin. A hydraulic jump stilling basin is used to dissipate kinetic energy by the formation of a hydraulic jump at the interface between a lined spillway and the downstream channel. The stilling basins are typically lined with concrete to avoid scour and erosion. *Design of Small Dams* (Reclamation 1987) documents typical jump style stilling basins for different ranges of Froude numbers (F_r). Froude numbers are related to the kinetic flow factor of the discharge entering the basin. Typical Reclamation stilling basins are summarized in Table 1, which also references Figures 14 through 17. It should be noted that stilling basins often have minimum tailwater requirements for correct operation.

Table 1: Typical Reclamation Stilling Basins

Basin Type	Description	Applicable Range of Froude Numbers
Basin I (Figure 14)	Hydraulic jumps on horizontal aprons	$1.7 < F_r < 2.5$
*Basin II (Figure 15)	Stilling basins for high dams and earth dam spillways	$F_r > 4.5$
**Basin III (Figure 16)	Short stilling basins for small spillways	$F_r > 4.5$
Basin IV (Figure 17)	Transitional jump stilling basins	$2.5 < F_r < 4.5$

* Not often applicable for small dams; ** Incoming velocities not to exceed 50-60 fps

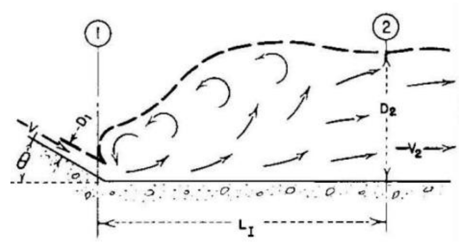

Figure 14: Type I Hydraulic Jump on Horizontal Apron

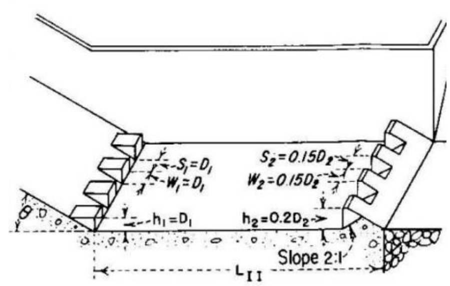

Figure 15: Type II Stilling Basin

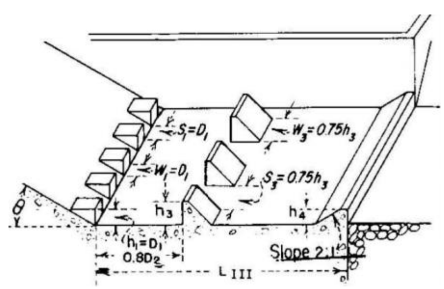

Figure 16: Type III Stilling Basin

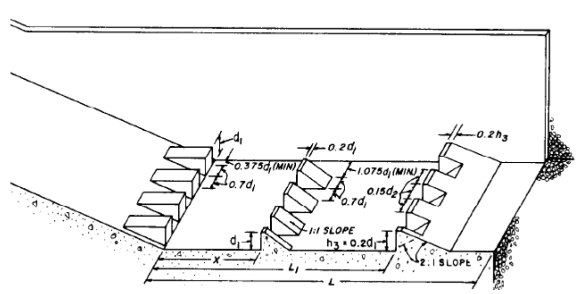

Figure 17: Type IV Stilling Basin

Roller Buckets and Flip Buckets

Roller bucket and flip bucket terminal structures are not described herein, as they are typically provided with large dams/spillways and concrete dams.

Impact Basins

An impact style stilling basin does not depend on tailwater and can be used on either a conduit or open channel conveyance system. Energy dissipation is accomplished by discharging the high velocity jet into a vertically hanging baffle. Care must be taken not to submerge the outlet conduit with tailwater and inhibit downstream venting unless alternate means for venting the outlet conduit are provided. Typically, the area downstream of the baffle is protected with riprap. An impact basin is typically located so that the tailwater is approximately half way up the baffle. An example of an impact basin at the end of a conduit is shown as Figure 18. An impact basin can also be fitted to a rectangular chute.

Figure 18: Impact Basin

Plunge Pools

A plunge pool is the terminal structure defined by the location where a free overflow spillway or a flip bucket discharges into the downstream channel. Plunge pools can consist of either naturally forming scour holes in the channel, or can be artificially created by construction of a downstream sill or excavation into the streambed. Plunge pools can either be lined or unlined, depending on streambed materials and erodibility of the material with respect to the energy that must be dissipated. Lining usually consists of either concrete or riprap. The volume and depth of the hole are related to the range of discharges, the height of the drop, and the depth of available tailwater.

Downstream Channels

The stability of the downstream channel must be understood to guard against headcutting or sidecutting at the toe of the spillway and the potential to threaten the integrity of the spillway, river channel, or the dam itself.

The downstream channel can be described as natural or modified, and can be categorized as unlined rock or soil, armored, or vegetated or a combination of these.

The downstream channel type, natural river geomorphology, and the behavior of the tailwater must be considered with regard to the tailwater requirements for the terminal structure.

References

[1] State of Colorado: Department of Natural Resources. (2007). *Rules and Regulations for Dam Safety and Dam Construction*.

[2] United States Department of the Interior: US Bureau of Reclamation. (1987). *Design of Small Dams*.

[3] United States Department of the Interior: Bureau of Reclamation. (1984). *Engineering Monograph No. 25: Hydraulic Design of Stilling Basins and Energy Dissipators*.

[4] United States Department of the Interior: Bureau of Reclamation. (2011). *Appurtenant Structures for Dams (Spillway and Outlet Works) Design Standards*.