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Impacts of Tailwater on the Design of Several Stilling Basins in the USA

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ABSTRACT

The dissipation of excess energy from flows exiting a spillway is often needed to prevent or reduce to acceptable levels conceivable negative impacts to the downstream channel, spillway, and dam (e.g., erosion, undermining). The optimization of a hydraulic jump type stilling basin using general-purpose, published design methodologies (i.e., USBR, SAF, etc.) for a project can be challenging, as these methodologies may not account for all site specific conditions and structure formulations by designers. Also, it is not often clear to a designer as to which flow rates (and corresponding flood events) will have the greatest influence on the basin geometry and features (i.e., jump formation location and stability). This can be further obscured for projects where a high tailwater condition is predicted during flood events.

This paper presents several recent dam rehabilitation projects where a high tailwater impacted the designs of the stilling basins. Each project features a different spillway, chute, and basin configuration. An overview of each site and summary of key challenges encountered during the design of the spillways and stilling basins is included. In addition, a discussion of which design methods were selected, why they were selected, and additional measures that were taken to address the uncertainties at the site is included. This documentation of unique site conditions and design methodologies for stilling basins is intended to show the importance of collaboration between the designer and the owner in selecting a design approach for a specific situation.

Keywords: *spillways, energy dissipation, tailwater, hydraulic jump, stilling basin*

1. INTRODUCTION

Each dam site and spillway system has unique characteristics. This includes factors such as layout, required spillway capacity and downstream tailwater conditions. In addition, the dam spillway systems are also frequently constrained by time and budget limitations. These constraints often lead to the designer using published predictive methods in less than ideal scenarios. The ideal solution to design the spillways and stilling basins would often be to use a physical model, Computational Fluid Dynamics (CFD) model, or combination of the two. The focus for the designs discussed in this paper is the calculation of the energy dissipation that is ultimately used to design a stilling basin. The size of the stilling basin is a critical consideration in the design process. It should be large enough to transition the flow to the downstream channel without endangering the integrity of the dam. However, to be cost-effective, the stilling basin should not be larger than necessary to adequately dissipate energy.

Many times, due to the unique site characteristics, calculating the energy dissipation system requires using predictive methods as approximations of the site. This often requires a piecemeal approach of mixing different methods since many sites do not fit one particular method. For example, one method would be used to calculate the flow over the spillway crest, a different method to account for losses at the bottom of the weir onto the concrete pad, and a third method would be used to account for the losses down a stepped section of the chute. Another condition that is difficult to account for is designing a stilling basin for tailwater depths that vary significantly from the conjugate depth. At some sites, the stilling basin can be raised or lowered to improve this relationship; however, there are limits to how much this can be done. This can lead to over design of stilling basins at locations with high tailwater.

The following sections discuss four projects where the energy dissipation was analyzed and the methods used to design the stilling basins.

2. TERMINOLOGY

The spillways and stilling basins discussed in the following sections were designed using a specific design storm determined by the appropriate regulatory agency. The design storms are related to the Probable Maximum Precipitation (PMP) or the Probable Maximum Flood (PMF). The PMP is theoretically the largest storm event that can occur at a particular location for a particular duration. The PMF is the flood resulting from the PMP. Frequency storms were also taken into consideration.

Designing a stilling basin involves calculating the appropriate length and elevation of the basin as well as the type of basin. Factors taken into account to design the basin are the depth of tailwater, the depth of flow downstream of the hydraulic jump, the depth of flow upstream of the hydraulic jump, and the energy head. For the purposes of this paper, the following terms will be used. The tailwater is the depth of flow downstream of the dam for a specific flow rate or storm based on a hydraulic model of the downstream channel. The conjugate depth is the depth of flow downstream of the hydraulic jump. The entrance depth is the depth of flow upstream of the hydraulic jump. The energy head measured as a depth is the metric used to calculate the energy in the system at a given location. The residual energy head is the energy head at the entrance of the stilling basin.

Three design approaches are discussed in conjunction with the case studies; physical models, CFD models, and predictive methods. A physical model study is a scale model of the proposed design usually built by a hydraulic research lab. Various specified flow rates are passed through the proposed structure to evaluate the impacts. A CFD model is a two- or three-dimensional computer representation of the proposed design. Like the physical model, the CFD model evaluates various flow rates as they are passed through the proposed structure. If both a physical and CFD model are used for the same proposed structure, the physical model can be used to calibrate the CFD model parameters. The term predictive model, for the purpose of this paper, refers to equations and methods published in journals and manuals. These are most commonly used at the conceptual design phase, for more simple designs, and in cases when the design budget or time frame does not allow for a physical or CFD model.

3. CASE STUDY #1: LAKE TOWNSEND DAM

3.1. Site Description

Lake Townsend Dam is the primary water supply dam for the City of Greensboro, North Carolina. The dam has a 7-cycles labyrinth spillway and an earthen embankment. The earthen embankment is designed to overtop by up to 1.5m (5-ft) to pass the required design storm of the ¾ PMP in accordance with North Carolina Dam Safety regulations. The labyrinth contains two cycles with a crest elevation 0.3m (1 ft) lower than the other five cycles. Downstream of the lowered labyrinth section are three steps that are from upstream to downstream 1.2m (4-ft), 2.4m (8-ft), and 1.2m (4-ft) high. Downstream of the higher labyrinth cycles are two steps, one 1.2m (4-ft) and one 1.8m (6-ft). The steps were configured to match the valley’s shape so that the amount of excavation required to install them was reduced. The configuration also allowed the flow to be in line with the downstream stream channel under typical flow conditions.

The tailwater at the site is significant for even relatively small storms. Under normal conditions, the tailwater is located at the bottom of the second step downstream of the lower cycles, or 1.2 m (4-ft) above the stream bed. During the 50-year storm, the tailwater is located at the base of the labyrinth walls, or 4.9 m (16-ft) above the stream bed. During a storm equal to the spillway capacity (approximately 60% of the Probable Maximum Precipitation), the tailwater is located at the normal pool elevation (crest of lower cycles). When the dam reaches full capacity, including the overtopping of the embankment, the tailwater is located just below the top of the embankment. One important factor causing the high tailwater at this site is a run of the river dam located 2,400 m (2 miles) downstream that has a crest elevation only 0.5 m (1.5 ft) lower than the low section of the stilling basin at Lake Townsend.

Figure 1. Overview of Lake Townsend Dam

3.2. Discussion of Design Approach

The owner of Lake Townsend Dam prioritized doing the work upfront to design an efficient dam and reduce costs during and after construction. This resulted in an investigation and design budget and schedule that allowed for a physical and three-dimensional CFD model study. The owner was very interested in performing the model studies to improve overall design and reduce the construction budget.

During the design of Lake Townsend, the energy dissipation was designed using a combination of a 1:21 scale physical model study and CFD modeling due to the sites uniqueness and the extreme amount of tailwater at the site. The physical model was used to evaluate the effects of tailwater on the labyrinth weir and provide calibration values for the CFD model. The both the physical and CFD models were used to evaluate various alternatives for the energy dissipation.

A stepped chute or series of drops was proposed downstream of the labyrinth weir. This configuration is believed to be more cost effective to construct than a sloping chute and traditional energy dissipation structure. The steps provide energy dissipation, particularly for lower flows. For higher flows, the tailwater tends to submerge the flow downstream of the weir, reducing the magnitude of energy dissipation. Several configurations were evaluated using the CFD and physical model such as 1.2 m (4-ft high) steps, 0.6 m (2-ft) high steps, and a sloping apron. The selected configuration consists of a four-foot drop to a sixteen-foot flat section to an eight-foot drop. A third four-foot drop will be provided at the north end of the spillway where low stage flows are directed into the downstream channel. The CFD model results indicated that for flows greater than approximately 50-year storm, the high energy flow did not reach the channel bottom. The selected configuration was found to be more effective at dissipating energy than the other options tested. Without the physical and CFD models, the stilling basin would likely have been overly conservative by being sized to pass a much larger storm event.

4. CASE STUDY #2: FOX CREEK MPS #4

4.1. Site Description

Fox Creek MPS #4 is located near Flemingsburg, Kentucky. The dam is used for flood control and recreation. The primary spillway is a pipe and riser that discharges into the concrete stilling basin. The dam consists of an earthen embankment and a 90 m (295 ft) wide Roller Compacted Concrete (RCC) ogee shaped auxiliary spillway over the embankment. The auxiliary spillway discharges into a chute that converges by 15 degrees down the stepped section to the stilling basin. The stilling basin is a United States Bureau of Reclamation (USBR) Type II stilling basin with two stages. A Type II stilling basin is a concrete apron with an end sill. The two stages were designed so that the primary spillway outlet would discharge in line with the downstream channel. Under normal conditions, the tailwater is located 0.3 m (1-ft) above the low stage of the stilling basin and 0.9 m (3 ft) below the second stage of the stilling basin. During the ¼ PMP storm, the tailwater is located 0.2 m (0.7 ft) above from the second stage of the stilling basin. During the design storm (PMP), the tailwater is located 0.12 m (0.4 ft) above the first step, located immediately downstream of the ogee spillway slab, so, essentially, the entire stepped section of the spillway chute is submerged.

Figure 2. Overview of Fox Creek MPS #4

4.2. Discussion of Design Approach

The owner of Fox Creek MPS #4 was primarily concerned with finishing the project by a specific deadline. The project was funded by the American Reinvestment and Recovery Act of 2009. This funding was designated for shovel-ready projects. For Fox Creek MPS #4 rehabilitation to be considered shovel ready, the design had to be submitted for review 4 months after the geotechnical investigation was completed. If this deadline was not met, the funding would be reallocated to another project. Therefore, a physical or CFD model study, which would have been the preferred design method, was not completed. Instead, predictive models were used as the primary design tool.

The second main concern at the project site was the property boundaries. The dam owner's property boundary did not extend far beyond the toe of the dam or to the sides of the dam. To address the limited boundary and the short schedule, the dam layout was completed initially to fit it in the site, and then analyzed to make sure it would safely convey the design storm. If the design did not meet the requirements, the property acquisition process may have caused the deadline to be missed. To keep the structure within the property limits, steps were added to the downstream spillway slope to provide some energy dissipation and decrease the stilling basin length.

The primary method used to calculate step dissipation for Fox Creek MPS #4 was Dr. Sherry Hunt's paper "Energy Dissipation for Flat-sloped Stepped Spillways Using New Inception Point Relationship" from the 2009 Proceedings of the ASDSO Annual Conference. Hunt's physical model in this study has a 4H:1V slope, and the results are considered applicable to slopes ranging from 4H:1V to 2.5H:1V. The spillway slope at Fox Creek MPS #4 was 2.5H:1V, so this method was considered applicable. Hunt's procedure in this paper did not take into account the converging walls. This was one factor in the decision to design the walls for the PMF and the stilling basin for the 2/3 PMF. Using Hunt's procedure to evaluate the energy dissipation the steps provided, the stilling basin that was contained within the site was considered adequate.

Because this method did not account for the converging walls, an additional predictive method and a similar model study were also considered. The predictive method used was presented by Hubert Chanson in Appendix 7 of his book titled "Hydraulics of Stepped Chutes and Spillways." This method is considered to be appropriate for steep slopes. The stepped section of the proposed auxiliary spillway for Fox Creek MPS #4 has a slope of 2.5H:1V. This slope often is or is near the dividing line for what is considered to be a steep slope versus a flat slope in the methods developed to analyze stepped spillways (Chanson 2002). In addition, Chanson specifies that this method is to be used for a preliminary design. The results of this method were very similar to the results using Hunt's method and agreed that the design that fit the site was sufficient.

One of the stepped chute alternatives evaluated in the Lake Townsend CFD model was very similar to the proposed design of Fox Creek MPS #4. The Townsend alternative used 1.2 m (4-ft) high steps on a 2.5H:1V slope with a very similar unit discharge and tailwater location as Fox Creek. Because of the high tailwater during the design storm, we anticipated that the energy would dissipate prior to reaching the downstream end of the stilling basin. The Townsend CFD model alternative similar to the Fox Creek MPS #4 site indicated that this was the case. The results of the Townsend CFD model were used as a qualitative check that the proposed design in conjunction with the other calculations appeared to safely pass the required design storm.

Because the site has characteristics that did not fit a specific predictive model procedure, two predictive models and a similar CFD model were used to ensure that the design that fit within the property boundaries of the site was appropriate. Using a CFD and physical model may have allowed a more effective design to be used; however, the owner's main concern was ensuring that the funding would be available. If the deadline had not been met, funding would likely have been suspended, potentially leaving a dam with inadequate spillway capacity in place.

5. CASE STUDY #3: BULLOCK PEN DAM

5.1. Site Description

Bullock Pen Lake Dam is located in Crittenden, Kentucky. The dam retains Bullock Pen Lake, which is used for recreation and water supply for the town of Crittenden. Bullock Pen Lake Dam was constructed in 1953. Within a few years after construction and shortly after initial filling of the reservoir, erosion of the shale in the excavated rock spillway channel was observed.

The proposed structure will consist of a reinforced concrete labyrinth spillway over the current dam embankment. The labyrinth spillway will consist of 12.5 cycles and a total width of 79 m (260 ft). The labyrinth has two stages. The first stage will consist of 4 cycles at normal pool elevation, and the second stage will consist of 8.5 cycles with a crest 0.3-m (1-ft) higher than the normal pool elevation of the lake. The labyrinth spillway will discharge into a stepped chute and then into a USBR Type 1 stilling basin located at the toe of the embankment. Flows from the stilling basin will discharge into a riprap-lined outlet channel. Under normal conditions, the tailwater will be located 0.3-m (1-ft) above the low stage of the stilling basin and 0.9-m (3-ft) below the second stage of the stilling basin. During the 10-year storm, the tailwater will be located at the elevation of the lowest step of the chute. During the PMP, the tailwater will be located 0.27-m (0.9-ft) above the labyrinth spillway slab, submerging the stepped section of the spillway chute.

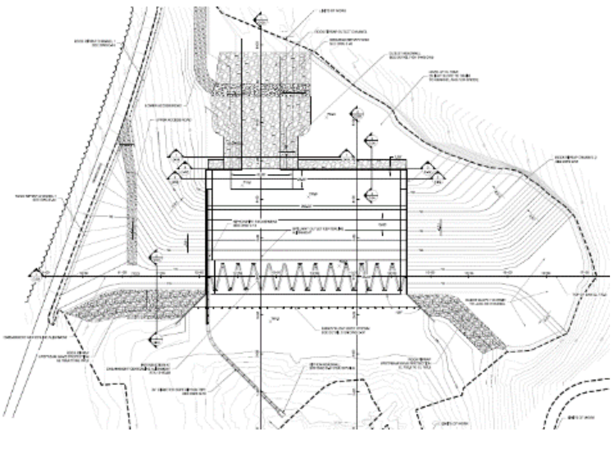

Figure 3. Proposed Layout of Bullock Pen Dam

5.2. Discussion of Design Approach

Due to the site complications, both a CFD model and predictive methods were used to analyze the energy dissipation at this site. The owner's schedule allowed time for the CFD modeling; however, there was not time or funding available to do a physical model. The design approach was to design the stilling basin using the predictive methods and use the CFD model to check the results of the predictive methods for reasonableness.

A piecemeal approach was used to design the stilling basin. The energy head loss resulting from the fall from the crest of the labyrinth to the base of the labyrinth wall was estimated using a method developed by Lopes (2009). The energy head loss down the stepped chute was estimated using Hunt's 2014 work. The selected stilling basin was a USBR type 1 basin, which is a concrete apron.

The CFD model showed that the hydraulic jump occurred over the stepped chute due to the high tailwater. The energy dissipation was calculated to be less than the predictive models; however, the velocity of flow at the exit of the stilling basin was lower than predicted. This is most likely do to the high tailwater at the site that the predictive models do not take into account. The results of the CFD model confirmed that the spillway layout designed using the predictive methods is appropriate for the site conditions.

6. CASE STUDY #4: SALEM LAKE DAM

6.1. Site Description

Salem Lake Dam retains Salem Lake, which is the second largest source of drinking water for the City of Winston Salem, NC. The lake is also used for recreational purposes. Salem Lake Dam consists of a concrete gravity dam. The dam consists of an overflow section and a non-overflow section. The overflow section consists of a conventional concrete ogee spillway that has two stages, the first one at normal pool and a second one (the high-stage) located on either side of the low-stage weir with the crest at 0.5 m (1.7 ft) above normal pool. The downstream face of the overflow section consists of steps. The dam's non-overflow sections are located on either side of the overflow section. Zoned earthen embankments tie into the non-overflow sections out to the abutments. The non-overflow section and the earthen portions have a crest 3.8 m (12.5 ft) above the normal pool. The overflow section of the dam has an ogee shaped crest. During the ½ PMP storm, the tailwater submerges the spillway by 0.12 m (0.4 ft).

Figure 4. Overview of Salem Lake Dam

6.2. Discussion of Design Approach

Salem Lake was analyzed using predictive methods primarily due to the relatively simple design and the results of the rock scour analysis. Energy Dissipation was analyzed to avoid scouring of the downstream area. This scour can threaten the integrity of the dam if it becomes extensive. During the geotechnical investigation, the stream bed was found to have good quality gneiss. This discovery prompted an analysis performed by Dr. George Annandale using his method (Annandale 2006). This procedure entailed comparing the erosive capacity of the water that will flow over the dam spillway and the erosion resistance of the rock at the dam abutments and foundation. The analysis concluded that the rock is unlikely to scour during the design storm flows. The calculations took the downstream tailwater into account.

After discussing the results with the owner, the decision was made to have a rock-lined stilling basin for a storm smaller than the design storm. This decision was made because if the stilling basin's capacity was exceeded, it would not pose a dam safety hazard. After comparing the difference between the upstream reservoir elevation and the downstream tailwater elevation for various storm events, the 500-year storm was selected.

7. CONCLUSIONS

The design methods for a project can be limited by external factors such as time, funding, property boundaries, or a combination of factors. In these cases, consideration should be given to the complexities of the site and structures that may not be taken into account with the method or methods selected. Conveying the unknown effects of these factors should be discussed with the owners so that they understand the risk they are taking on with the selected design. In addition, the owner should be made aware of measures that could be taken in advance of, during, or after a major flooding event when the design limits are tested.

8. ACKNOWLEDGMENTS

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- City of Greensboro, NC
- USDA-NRCS Kentucky
- Commonwealth of Kentucky
- City of Winston-Salem, NC

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