Performance of Type III Stilling Basins for Stepped Spillways

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ABSTRACT

Energy dissipation within hydraulic structures continues to be one of the major issues facing the designer of new or rehabilitated facilities, such as for overtopping protection of embankment dams. The energy dissipation characteristics of stepped spillways have been well documented, both for low- and high-head dams.

Interestingly, much of the generalized research on stepped channels and spillways over the past few decades, while concerned with the amount of energy dissipated on the steps themselves, has contributed very little to generalized design criteria for terminal dissipation structures/stilling basins. Many site specific studies have included work on modifications to stilling basins to account for the increased energy dissipation on the steps, typically resulting in a shortening of the basin length. Others have included some stilling basin parameters within their studies. A few studies have attempted to provide generalized design guidance for the use of specific types of stilling basins with stepped chutes and spillways.

This paper will focus on recent studies at the Reclamation laboratory that evaluated the application of smooth channel design criteria for Type III stilling basins to a variety of stepped spillway slopes. While there is a lack of specific generalized studies for stilling basin performance over the range of all types of stepped spillways that exist, there appears to be adequate data available to allow the designer to select and size an appropriate stilling basin for most types of stepped spillways currently in use, including RCC overtopping protection systems.

Keywords: energy dissipation, stepped spillways, stilling basin, Froude number.

1. INTRODUCTION

Stilling basins or energy dissipation structures remain critical features of spillway design. No matter the size or type of spillway under consideration, a properly selected and sized stilling basin is necessary to protect the integrity of the structure, dam, and the downstream river channel. Since the advent of roller compacted concrete (RCC) in the 1980’s, many new and existing structures have been designed with stepped (either RCC or formed) spillways. These have typically been smaller or low-head structures typical of embankment dams. Numerous laboratory studies have looked into the hydraulic properties of stepped spillways and the benefit that results from increased energy dissipation on the stepped chute; however, few studies have looked at generalized design of appropriate stilling basins at the toe of a stepped spillway.
1.1. Background

In the late 1950’s Bureau of Reclamation (Reclamation) personnel (Bradley and Peterka, 1957a-f) published a series of 6 papers in the American Society of Civil Engineers (ASCE) Journal of the Hydraulics Division on the hydraulic design of stilling basins and their associated appurtenances. This work described many studies including both site-specific and applied research completed at Reclamation’s hydraulics laboratory in Denver, Colorado. The studies were further generalized and published as Reclamation Engineering Monograph No. 25 *Hydraulic Design of Stilling Basins and Energy Dissipators* by A.J. Peterka. This monograph was first published in September 1958 with the fourth and last revised printing occurring in January 1978 (Peterka, 1978).

Recent studies at Reclamation’s laboratory have focused on generalizing design procedures for Type III stilling basins for either smooth or stepped spillways. Frizell and Svoboda (2012) used a sectional model to measure stilling basin performance, in particular looking at sweep out characteristics and length requirements, and also studying the performance of a supercavitating baffle block that was being developed during the same time period. This paper provides a condensed presentation of that research, focusing on the basin performance while omitting discussion of the new baffle blocks.

The stilling basins that will be addressed in this paper are a class of structures that use fixed internal features to assist in the formation and stable performance of a hydraulic jump at the end of a high velocity spillway chute. Much of the background theory used in the work of Bradley and Peterka was concerned with the hydraulic jump forming on a horizontal floor (figure 1) and has been treated thoroughly by others. The depths at sections 1 and 2 of figure 1 are often referred to as conjugate or sequent depths and with the corresponding velocities are used to represent the conservation of momentum within the hydraulic jump. Based on the conservation of momentum, assuming uniform hydrostatic pressure and velocity distributions at sections 1 and 2 and neglecting the force of friction, the hydraulic jump can be expressed as:

\[
\frac{D_2}{D_1} = \frac{1}{2} \left( \sqrt{1 + 8F_1^2} - 1 \right)
\]

Where \( D_1 \) and \( D_2 \) are the sequent depths respectively at sections 1 and 2, \( F_1 = \frac{V_1}{\sqrt{gD_1}} \) is the Froude number at section 1, \( V_1 \) is the mean velocity at section 1 and \( g \) is the gravitational constant.

Figure 1. Design parameters for stilling basins include velocity and depth at section 1 (entering the stilling basin) and velocity and depth at section 2 (after the hydraulic jump).
The Type III stilling basin has general usage on canal structures, small outlet works, and small spillways. Identical to the Type II basin except for the addition of a row of baffle piers along the floor of the basin, increased energy dissipation allows for a considerably shorter basin for relatively small flows \( q \leq 18.6 \text{ m}^2/\text{s} \) \((200 \text{ ft}^2/\text{s})\) with limited incoming velocities \( V \leq 18 \text{ m/s} \) \((60 \text{ ft/s})\). Model studies have shown that the Type III stilling basin operated equally well for all Froude numbers above 4 provided the tailwater equals the full sequent flow depth. The monograph provided confident, conservative designs for basins falling within the guidelines found in the document. This was not to suggest that this type basin could not be used outside of these bounds, just that a specific model study would be recommended along with consideration for other possible factors (e.g., higher velocity flows) potentially affecting performance. The Type III basin used in these studies was sized based on Peterka’s criteria and detailed on figure 2.

![Figure 2. Layout of Reclamation Type III stilling basin from Peterka (1978).](image)

Many researchers have studied the enhanced energy dissipation on stepped chutes operating in the skimming flow regime, such as Stephenson (1991), Chanson (1994, 2002), Matos (2000), Boes and Hager (2003), Takahashi and Ohtsu (2012), Hunt and Kadyav (2014), Hunt et al. (2014), Chanson et al. (2015). The results of numerous site-specific model studies have shown that smaller, i.e., shorter, stilling basin lengths are required Houston (1987), Frizell (1990a, 1990b, 1992), Hunt (2008). Cardoso et al. (2007), Meireles et al. (2010) and Bung et al. (2012) studied particular features of Type III stilling basins at the terminus of steeply sloping stepped chutes. Some main findings of these studies were that the hydraulic jump downstream of a stepped chute stabilized much faster than in a Type I stilling basin, similarly as found downstream of smooth chutes; also, the performance of the basin with or without chute blocks was not dissimilar, suggesting that chute blocks would to be dispensable in Type III basins downstream of steeply sloping stepped spillways.

### 1.2. Experimental Setup

The main features of the model included a 0.45 m (1.5 ft) width flume of adjustable slope, a pressurized jet box (Schwalt and Hager 1992), a standard type III stilling basin with 0.45 m (1.5 ft) width, designed for a Froude number of 8 with incoming depth of 76.2 mm (0.25 ft), and an adjustable flap gate at the model exit for setting tailwater elevations, figure 3. Three slopes were tested, 14.04-, 26.57-, and 51.34-degrees above horizontal corresponding to...
4H:1V, 2H:1V, and 0.8H:1V respectively. At each slope, data were collected for both a smooth chute bottom and a stepped configuration with a step height of 38.1 mm (0.125 ft).

Figure 3. Stilling basin model with stepped chute at 26.57-degrees terminating in a Type III basin.

The jet box was used to provide high velocity inflow to the spillway chute in order to simulate larger Froude numbers than would be possible based on the available elevation difference. The box pressurizes and then the incoming depth on the chute can be adjusted, resulting in a rectangular flow passage formed by the chute bottom and walls and the upper gate lip of the jet box. Flow rates up to 0.283 m$^3$/s (10 ft$^3$/s) in the model were possible with a basic range of specific discharges from 0.25 m$^2$/s (2.7 ft$^2$/s) to 0.62 m$^2$/s (6.7 ft$^2$/s). Gradually varied or quasi-uniform flow conditions were likely attained at the downstream end of the 2H:1V and 0.8H:1V chutes, after comparing air concentration profiles at the chute end with a cross section further upstream with good agreement. Mean air concentrations for the smooth chutes were smaller than the similar sloped stepped channels indicating that uniform flow was not attained.

The basic test procedure consisted of setting the discharge ($Q$), incoming flow depth to the chute from the jet box, adjusting the tailwater such that the toe of the hydraulic jump was sitting over the top of the chute blocks for the case of the smooth chutes or a similar location for the stepped chute, and reading the stilling well to determine $D_2$. Air concentration profiles were measured on the chute near the basin entrance to find the mean (depth-averaged) air concentration $C_m$, determined by numerical integration of the profile from the invert or pseudo-bottom (stepped chute) up to the point where the local air concentration was 90% ($D_{90}$. The effective or equivalent clear water depth $D_t$ was then calculated from $D_t = (1-C_m)D_{90}$. For the stepped-chute cases, the tailwater elevation was also lowered to sweep-out conditions in the basin (toe of the jump located off the chute slope) to document the minimum acceptable tailwater.

2. RESULTS

Three channel slopes were tested with both smooth and stepped chutes, terminating in the same Type III stilling basin. Data are presented using the equivalent clear water depth at section 1, and in turn the incoming Froude number to the basin is calculated using this depth. Smooth chute data are shown in figure 4.
Figure 4. Smooth chute data with Type III verification data from Peterka (1978) shown in red. Peterka’s minimum tailwater (TW) data was 82.4-percent of sequent depth; Frizell and Svoboda (2012) data show best fit for all slopes at 75.1-percent of the sequent depth.

Data from the stepped chute for the three different slopes are shown in figure 5. Similar specific discharges were used for each data set; note the incoming Froude numbers are considerably lower than for the smooth chute. This occurs because incoming velocities are reduced and equivalent clear water depths are increased at the point of measurement due to energy dissipation on the steps. The three stepped chute data sets compare well to the Type III verification sweep-out data from the smooth chutes.
Figure 5. Stepped chute data with Type III (smooth) verification data from Peterka (1978) shown in red. Peterka’s minimum tailwater (TW) data was 82.4-percent of sequent depth; Frizell and Svoboda (2012) data for all slopes are 81.8-percent of the sequent depth.

3. DISCUSSION

The initial analysis of the data consisted of duplicating plots found in Monograph 25 (figures 4 and 5), and using the smooth chute Type III verification data that is presented. The Type III verification data reflects designs with the tailwater at full sequent depth (red line) while the tailwater at sweep out or Peterka’s minimum acceptable tailwater is about 82.4-percent of the full sequent depth of an unconstrained jump (black line). Interestingly, the data from Frizell and Svoboda (2012) when best fit with a linear regression, plot at about 75.1-percent of the full sequent depth, regardless of slope. This data was not taken at what could be called sweep out but was rather at a tailwater condition where the toe of the jump was still up on the slope of the chute and covering the chute blocks for each of the various
slopes. Measurement methods, particularly for incoming depth, $D_1$, likely have the largest impact on these data, especially at high Froude numbers. Air entrainment can be substantial even on a smooth chute. The measurement of $D_1$ by Bradley and Peterka was an average of several visual observations of a very erratic water surface using a point gage. While the data may be consistent within their study, they likely overestimated the incoming clear water depth which has been used for comparisons with the present study. Overestimation of $D_1$ by 5% will affect both the $D_2/D_1$ ratio (dropping it by the same percentage) and $F_1$ (dropping it by 7%). These changes move the best-fit regression line to the left, providing the impression of a higher required tailwater for a given $F_1$.

The study of Frizell and Svoboda (2012) was carried out at a single design point. The stilling basin geometry was sized based on an incoming Froude number, $F_1=8$, and incoming depth $D_1=76.2$ mm (0.25 ft). Unlike the Monograph 25 studies where for each change in $F_1$ the basin dimensions also changed, our study would be more typical of a normal design, where a design value is chosen, the basin is sized, and then performance evaluated over a range of $F_1$.

Figure 6 shows a plot of $F_1$ versus the ratio of basin length to tailwater. Data from the stepped chutes are plotted in these terms, showing that the basin length tested was larger than what would be needed for the Type III basin based on Peterka’s (1978) design information. The near vertical orientation of the current data sets emphasizes the fact that the basin length was not modified depending on changing $F_1$. In each case as $F_1$ was varied, only the resulting $D_2$ changed. As Froude number increased within each data set the values of $L/D_2$ approached the curve representing Type III basins. These findings suggest that a shorter stilling basin would be possible for the reduced Froude number flows (and consequently reduced flow depths $D_2$) typical of the stepped chutes.

Figure 6. Stepped chute data plotted versus verification data for Type I, II, and Type III stilling basins, Peterka (1978). Model basin design point shown, $F_1=8$, $D_1=76.2$ mm, $L_{iii}=2.159$ m (from Peterka assuming full sequent depth).
Figure 7 shows both smooth and stepped data on the same plot. Note that between $F_1$ of 4 to 9, both data sets follow a similar trend. Slope does not appear to be a significant factor, so only the incoming Froude number (based on the equivalent clear water depth) is needed to design a type III basin for either a smooth or stepped chute. This finding indicates that traditional criteria can be used to size a stilling basin for a stepped chute provided that $D_1$ and $F_1$ can be estimated at the toe of the spillway. Several empirical methods are available to provide these estimates (e.g., Matos 2000, Boes and Hager 2003, Meireles et al. 2009, 2011, Bung 2011, Pfister and Hager 2011, Takahashi and Ohtsu 2012, Hunt and Kadavy 2014, Hunt et al. 2014, Chanson et al. 2015).

Figure 7. Smooth and stepped chute data from Frizell and Svoboda (2012), for all slopes; Type III (smooth) verification data from Peterka (1978) shown in red. Peterka’s minimum tailwater (TW) data was 82.4-percent of sequent depth.
4. CONCLUSIONS

Recent model studies have extended the available data on performance of stilling basins with stepped spillways. Reclamation Type III stilling basins were tested at 3 different slopes over a large range of Froude numbers for both smooth and stepped chutes leading to the basin. This testing has allowed designers to confidently size a Type III basin for a stepped spillway of various slopes using Peterka’s existing design procedure for smooth chutes. The only requirements are that the designer is able to estimate the incoming equivalent clear water depth, from this and discharge requirements, the incoming Froude number, the sequent depth (TW) and the length of the basin can be calculated. Baffle sizes and spacing as well as the end sill elevations can be set. While the specific details of the Type III basin were tested, it is also reasonable to assume that most types of stilling basins can be confidently sized from smooth chute basin criteria as long as equivalent clear water variables are used.

5. REFERENCES


