Presented at:
33rd IAHR Congress
August 9-14, 2009
Vancouver, British Columbia, CANADA

Stilling basin performance for stepped spillways of mild to steep slopes – Type III Basins

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ABSTRACT

Stepped spillways operating in the skimming flow regime are well known to result in higher levels of energy dissipation than would occur on a smooth chute of equal drop. Empirical modeling and analytical methods using equivalent friction factors based on the step roughness have been successful in predicting general hydraulic characteristics such as depth and mean velocity. However, using bulk properties to design standard stilling basins has not always been successful, especially for stepped spillways of milder slopes. A review of previous research including new laboratory hydraulic modeling and computational fluid dynamics model data are used to gain insight to possible explanations which seem to infer that the mean energy available may not be as important as the chute slope and vertical distribution of energy entering the stilling basin. Factors such as air entrainment and stilling basin type are also considered.

INTRODUCTION

The dissipation of energy at the base of traditional open chute spillways can be accomplished by several means. The two most common approaches are to use a flip bucket to force the flow away from the structure and allow energy dissipation in a plunge pool downstream from the dam and critical structures, or some type of structure at the end of the spillway chute to dissipate the remaining energy – the most common type forces a hydraulic jump, thus transforming the incoming supercritical flow to subcritical flow exiting the basin.

Conventional design guidelines size the basin in order for the tailwater depths in the downstream channel to be nearly equal to the elevation of the conjugate depth of the hydraulic jump. If the tailwater is too low, sweep out occurs and excessive scouring of the downstream riverbed and basin structure are possible. If the tailwater is too high, the jump is submerged, resulting in less than expected energy dissipation and potential for adverse standing waves within or downstream of the basin.

In an effort to optimize the basin design from performance and cost bases, structural components, such as chute blocks, baffle blocks, and end sills, can be added to control and stabilize the hydraulic jump. Using these components typically allows for the shortening of the basin and can increase the factor of safety for the possibility of sweepout.

Prior stilling basin research has mostly featured smooth chutes. Stepped spillways have often been considered to allow for shorter basin lengths due to the additional energy that is dissipated along the steps prior to entering the basin. Many researchers have measured and or calculated the net energy reduction due to the influence of the steps, but there has been little generalized work on stilling basin design criteria and what differences are exhibited between smooth and stepped chutes. Boes and Hager (2003) suggested that, as long as the mean velocity and unaerated flow depths are used in calculation of the Froude number, the traditional design criteria should apply. Cardoso, et.al. (2007) presented data for a standard type III basin without chute blocks for steep (0.75H:1V) smooth and stepped chutes and conclude that the dimensionless jump length falls within the scatter of the original data presented by Peterka (1978). Hunt (2008) has presented a variety of data for mildly-sloped stepped spillways however many of those featured converging sidewalls on the chute and simple type I stilling basins.

Recent studies on a mildly sloped (2.5H:1V) stepped spillway of high unit discharge (74 m^2/s), that terminates in a stilling basin with baffle blocks and endsill, has shown some inconsistencies in the application of standard smooth chute stilling basin design criteria. Physical model studies at scales of 1:26 and 1:48 have both shown that the basin would need to be longer than that predicted using Reclamation's Type III stilling basin design criteria (Froude number entering the basin using unaerated flow depth and reduced mean velocity of flow on the steps) to effectively contain the energy within the basin.

In this paper we discuss factors that may affect the design of standard stilling basins for stepped spillway chutes. Reanalysis of existing data, along with new physical and numerical model results are used to revisit how general hydraulic characteristics of stepped spillways can be used with traditional smooth chute stilling basin design criteria. The standard Reclamation Type III basin is featured.

The Reclamation Type III Basin

Design of standard stilling basins has received much attention in the past 60 years. Reclamation's type III stilling basin is a standard hydraulic jump-type basin with appurtances including chute blocks, baffle blocks, and an end sill. The addition of the baffle blocks in the first third of the basin length helps force and stabilizes the hydraulic jump to dissipate additional energy. The required minimum basin length is greatly reduced over a type I basin. Peterka (1978) documented the design criteria for a type III basin based on incoming Froude number; however, little consideration was given to a systematic determination of the effect of chute angle on stilling basin performance. Figure 1 represents the reanalysis of available smooth chute data for Type III basin performance as a function of incoming Froude number for various chute angles. Based on this representation of the data it would appear that mildly sloped chutes indeed require longer basins and stilling basin performance is dependent on chute angle. While this factor has a small affect on performance for smooth chutes, it is anticipated to have a more pronounced effect for stepped chutes. Thus, there are two primary issues at hand associated with required minimum basin length for improved stilling basin design: 1.) the effect of chute angle and 2.) the effect of vertical energy distribution.

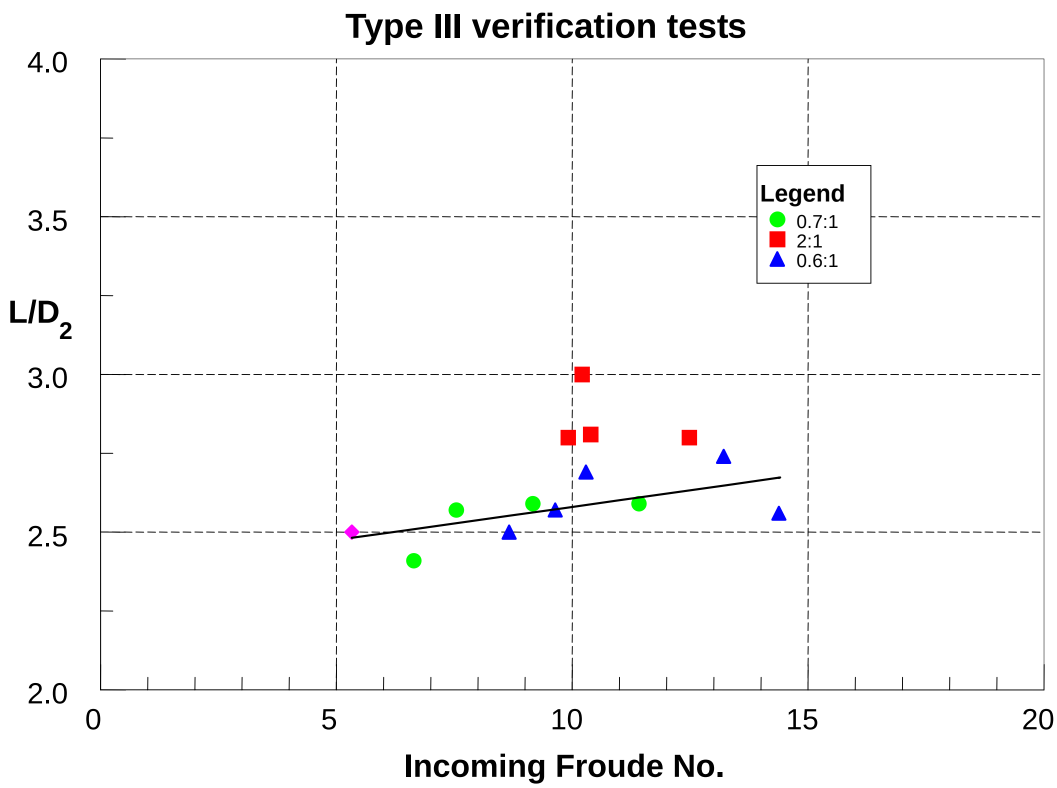

Figure 1: Nondimensional length versus incoming Froude number for smooth chutes of varying slope. Data are from verification tests by Peterka (1978).

Comparison of Stepped and Smooth Chute Hydraulics

The difference between stepped and smooth chutes lies mainly in the vertical velocity profile and hence vertical energy distribution. Clearly stepped chutes exhibit much smaller time-averaged velocities near the boundary in comparison with smooth chutes for the same unit discharge. Furthermore, increased flow depths result from the dissipation of energy imparted by the stepped geometry. However, recent experience suggests that such alterations do not appear to yield the commensurate reduction in stilling basin length requirements if one only considers Froude number based on mean velocity and flow depth entering the stilling basin.

Figure 2 shows the smooth and stepped chute velocity profiles for a large unit discharge case of 74 m^2/s. Also included are velocity profiles downstream of the toe which are representative of a swept basin condition. This direct comparison shows how the velocity profiles differ between stepped and smooth chutes.

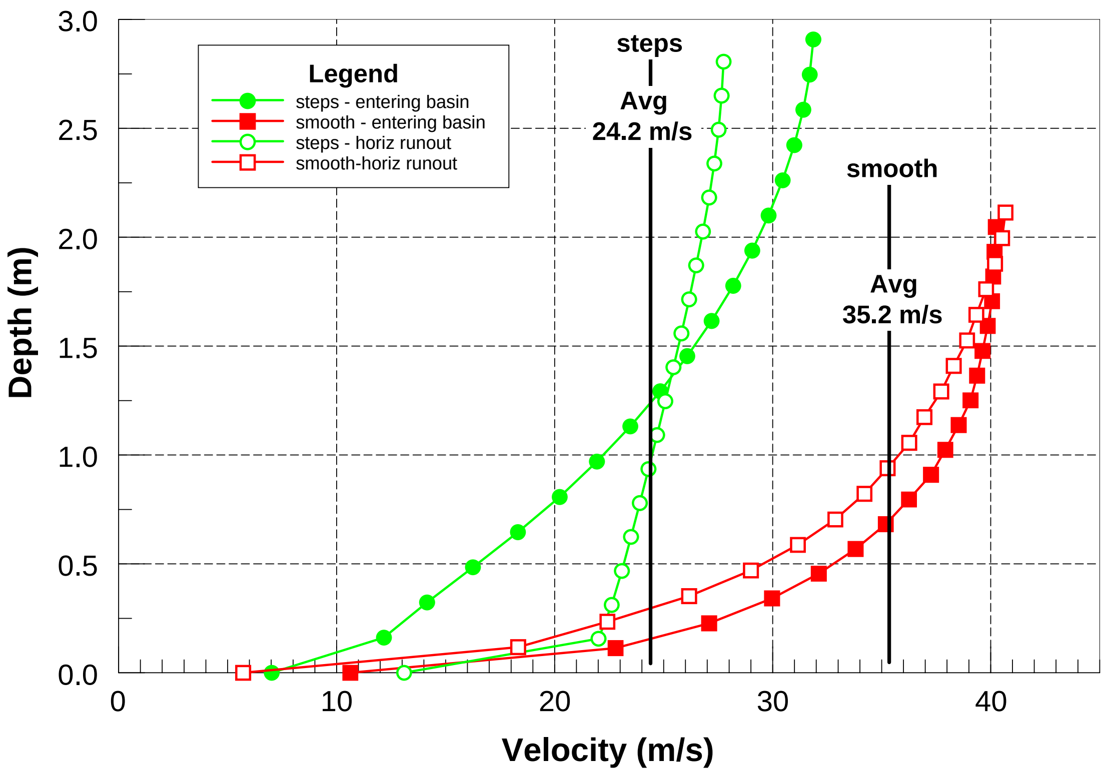

Figure 2: Centerline vertical velocity profiles for smooth and stepped chutes obtained from computational fluid dynamics modeling. Profiles entering the basin and profiles 15 m downstream on horizontal runout for stepped and smooth chutes at a unit discharge of q=74 m^2/s.

A significant decrease in velocity magnitudes (11 m/s on average) is apparent, especially in the lower half of the water column. This translates to a decrease in total energy of almost 42-percent for the stepped chute versus the smooth chute. The resulting Froude numbers based on entrance flow depth and mean velocity for each case may then be determined as 4.6 for the stepped chute and 7.8 for the smooth chute, corresponding to a predicted basin length of 39 m for the stepped chute and 58 m for the smooth chute. While stepped chutes produce a considerable reduction in Froude number, use of these values with generalized stilling basin design criteria do not appear to produce the expected reduction in stilling basin size based on scaled laboratory physical modeling observations.

Slope dependence and velocity profile effects

In reviewing the verification data from Peterka (1978) for the type III basin, the majority of the incoming slopes to the stilling basins were steeper than 1:1. Two thirds of the data points were for slopes of 0.6:1 and 0.7:1, slopes not unlike the typical RCC stepped spillways that have been studied and constructed in the past. The likely consequence of these steep slopes entering the stilling basin is that vertical velocity distribution has a reduced influence on stilling basin performance. Conversely, it is hypothesized that the flatter the slope the greater the influence of vertical distribution. Hence, for a stepped chute of mild slope, the significant decrease in the near boundary velocities reduces the energy dissipation effectiveness of the floor mounted baffle blocks, resulting in the need for a longer stilling basin. The same trend is apparent for smooth chutes; however, Cardoso et.al. (2007) show that a longer basin is required for the same Froude number for a stepped chute compared to a smooth chute for a slope of 0.75H:1V, figure 3, inferring a decreased effect of the slope with a stepped chute.

A review of the influence of incoming slope on basin length for type II and type V basins do not show any significant dependence on slope, figures 4 and 5. These basins do not have baffle blocks to assist in forcing and stabilizing the hydraulic jump. This independence on slope reinforces the idea that for a type III basin, that features floor-mounted baffle blocks, the vertical distribution of energy entering the basin is of more importance due to the effect of the baffle blocks.

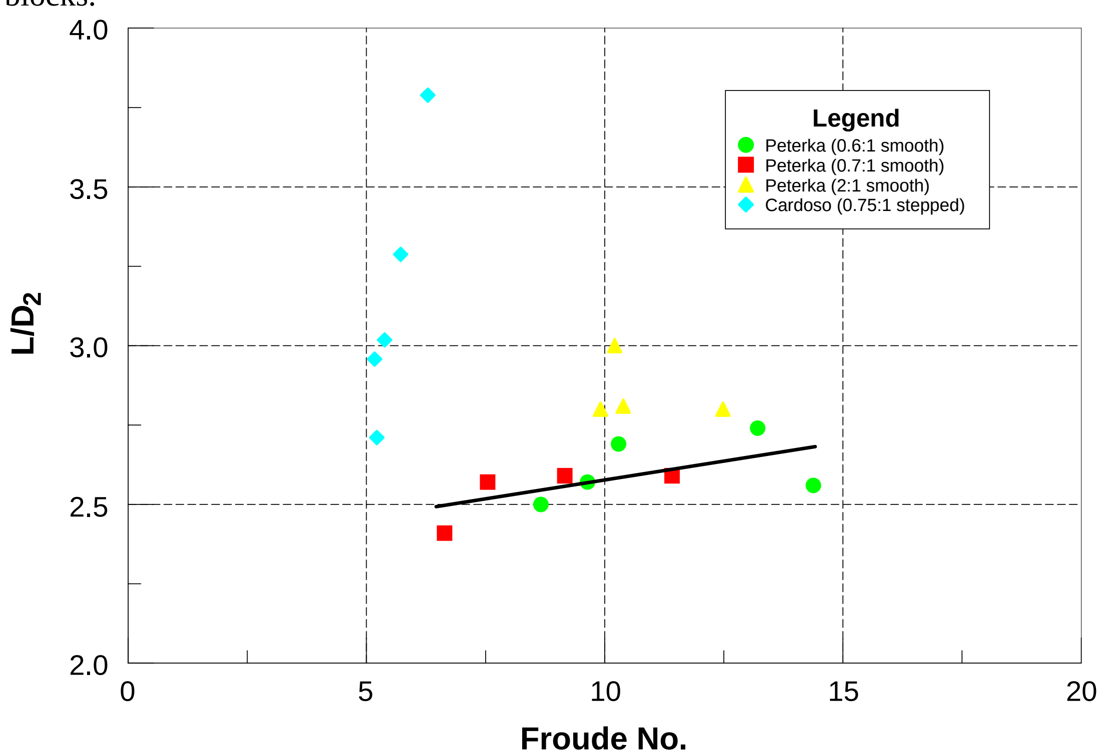

Figure 3: Peterka's smooth chute data along with Cardoso's stepped chute data for type III basins.

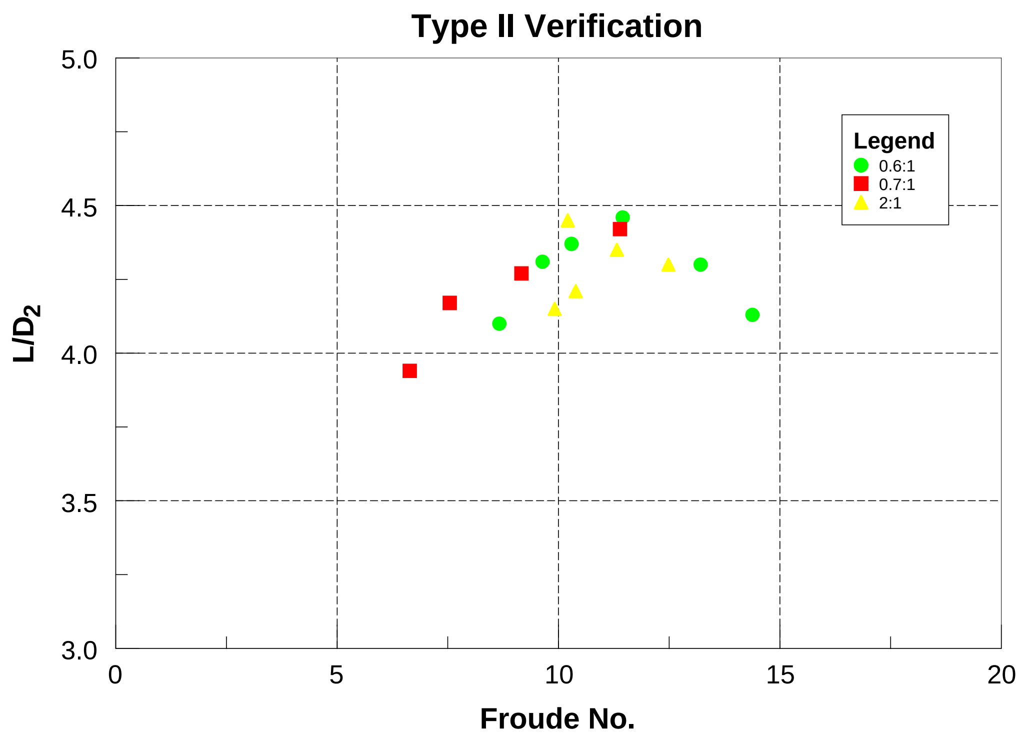

Figure 4: Verification data for Type II basin from Peterka (1978). Note there is a Froude No. dependence on L/D_2, but no apparent slope dependence.

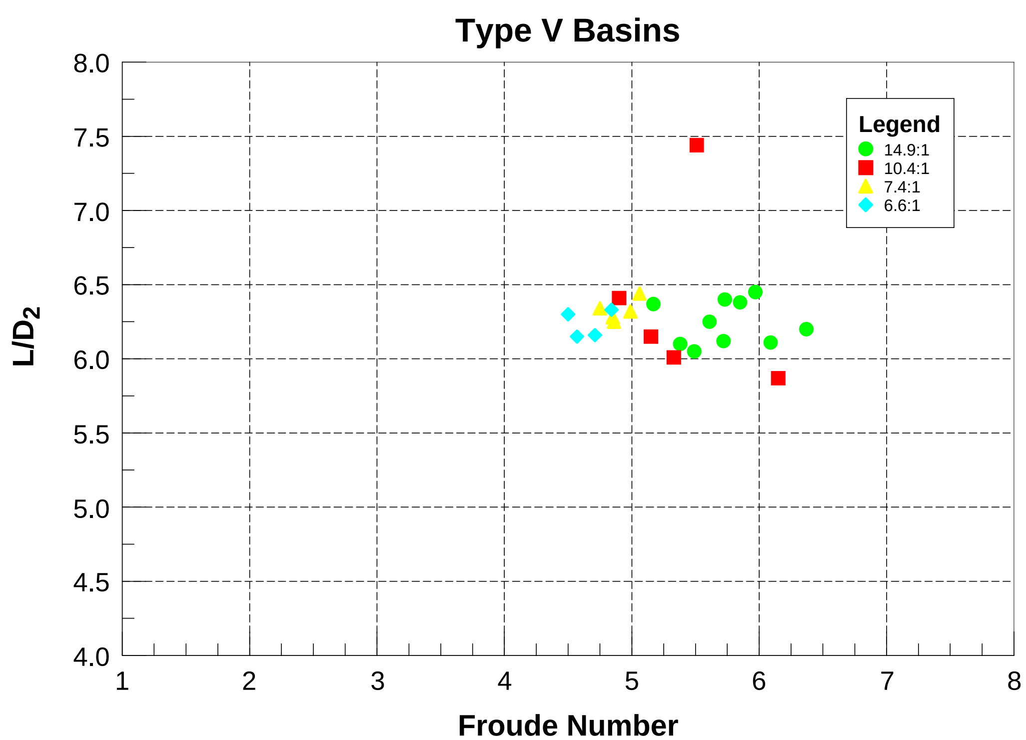

Figure 5: Verification data from Type V stilling basins from Peterka (1978). No apparent dependence of L on either Froude number or slope (note these are very mild slopes).

Conclusions

A review of the standard stilling basin design criteria presented by Peterka (1978) point out an apparent L/D_2 dependence on incoming slope (figure 1) for Type III basins. Looking at other types of standard basins, in particular type II and V, there does not appear to be slope dependence in this parameter. This dependence on chute angle for type III basins appears to be tied closely to the baffle blocks and the vertical distribution of energy (velocity) as flow enters the basin. The angle of attack on the basin floor appears to have a significant impact on the energy dissipation within the basin. As the slope is reduced, streamline curvature decreases resulting in a less abrupt transition and hence a localized reduction in energy dissipation.

The vertical velocity distribution in a stepped chute is significantly modified from that of a smooth chute and could lead one to infer that the effectiveness of the baffle blocks within a type III basin should be reduced. This reduction in energy especially within the lower one-third of the water column (figure 2), suggests a reduced impact of the baffle blocks in the overall performance of the stilling basin. Data from both steep and mild slopes indicate that a longer basin is needed for similar Froude numbers than a smooth chute would require.

Based on these findings it is clear that additional investigations are needed to 'tune' existing stilling basin design criteria. Further laboratory physical modeling to address the effect of slope on stilling basin performance is needed for smooth chutes and a systematic study of stilling basin requirements is needed for stepped chutes. The goal of these studies should be to integrate slope angle into generalized stilling basin design criteria for smooth chutes and develop new generalized stilling basin design criteria for stepped chutes; both of which are expected to improve applicability and cost effectiveness of stilling basin design and construction.

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