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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:

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

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

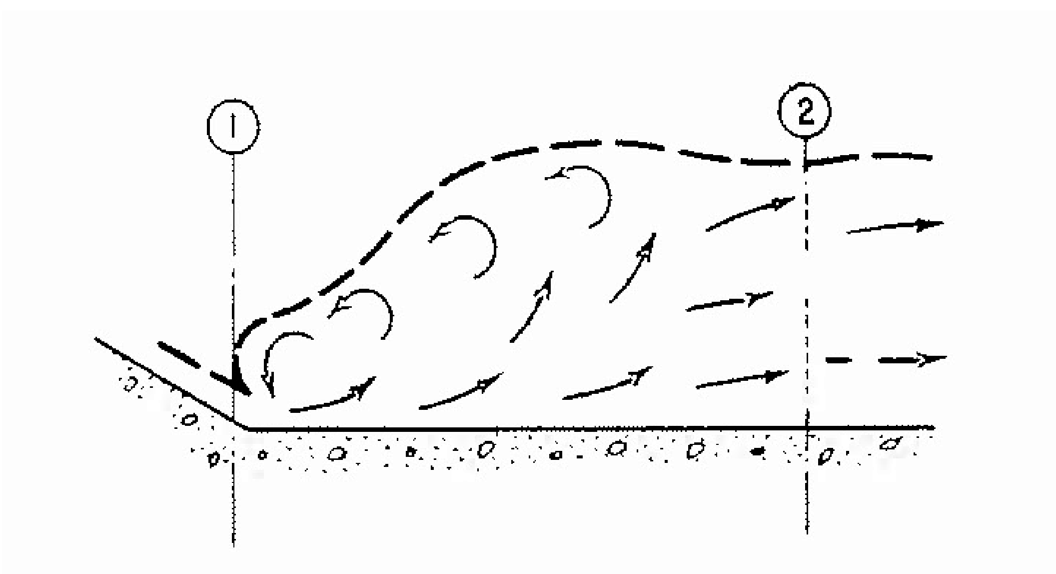

Figure 1. Design parameters for stilling basins include velocity and depth at section 1(entering the stilling basin) and velocity and depth at section 2 (after the hydraulic jump).

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 $q \leq 18.6$ m^2/s (200 ft^2/s) with limited incoming velocities $V \leq 18$ m/s (60 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.

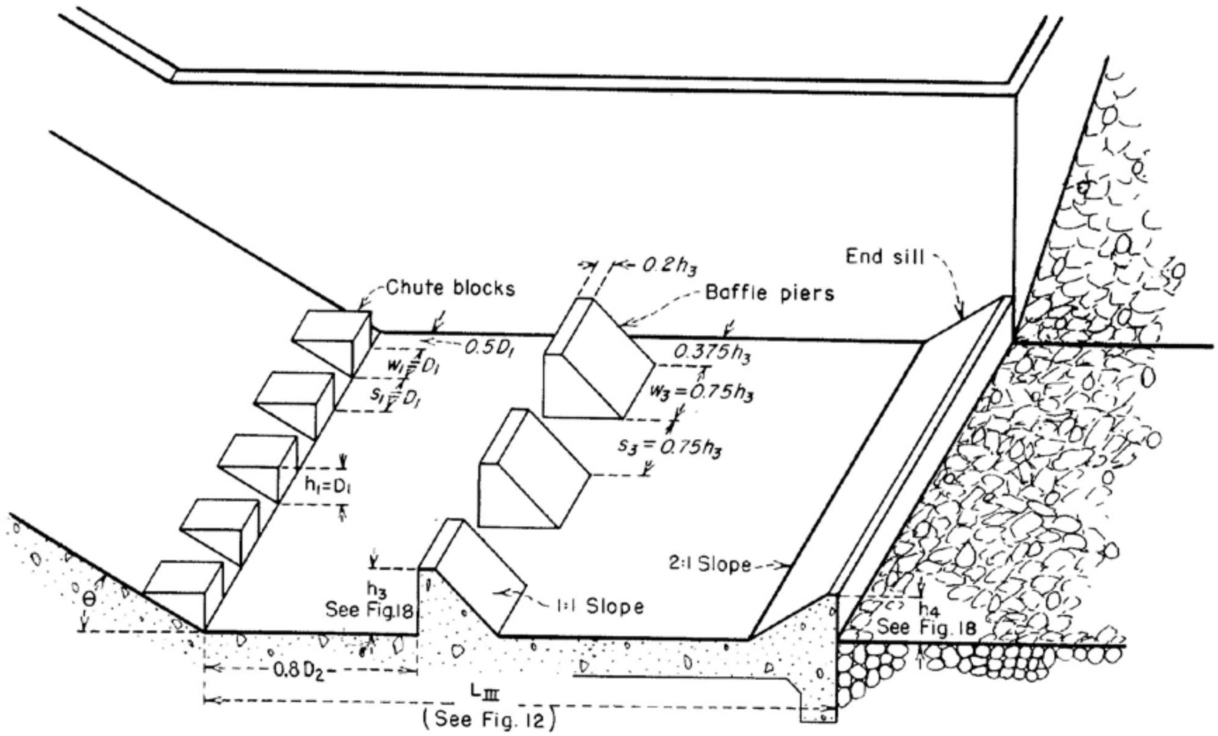

Figure 2. Layout of Reclamation Type III stilling basin from Peterka (1978).

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 Kadavy (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_1 was then calculated from $D_1 = (1-C_m) D_{90}$. 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.

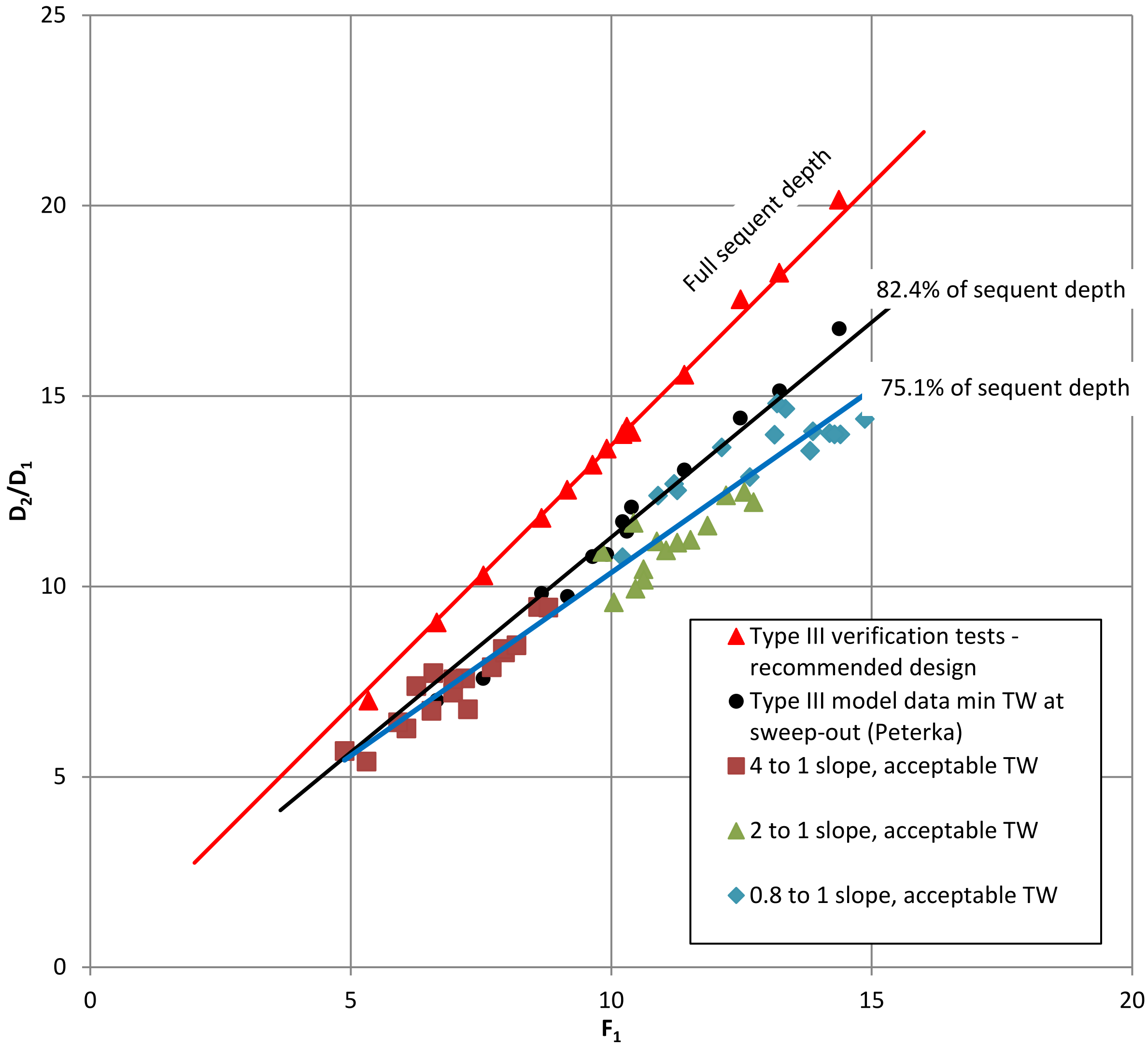

Figure 4 . Smooth chute data with Type III verification data from Peterka (1978) shown in red. Peterka's minimum tailwater (TW) data was 82.4-percent of sequent depth; Frizell and Svoboda (2012) data show best fit for all slopes at 75.1-percent of the sequent depth.

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.

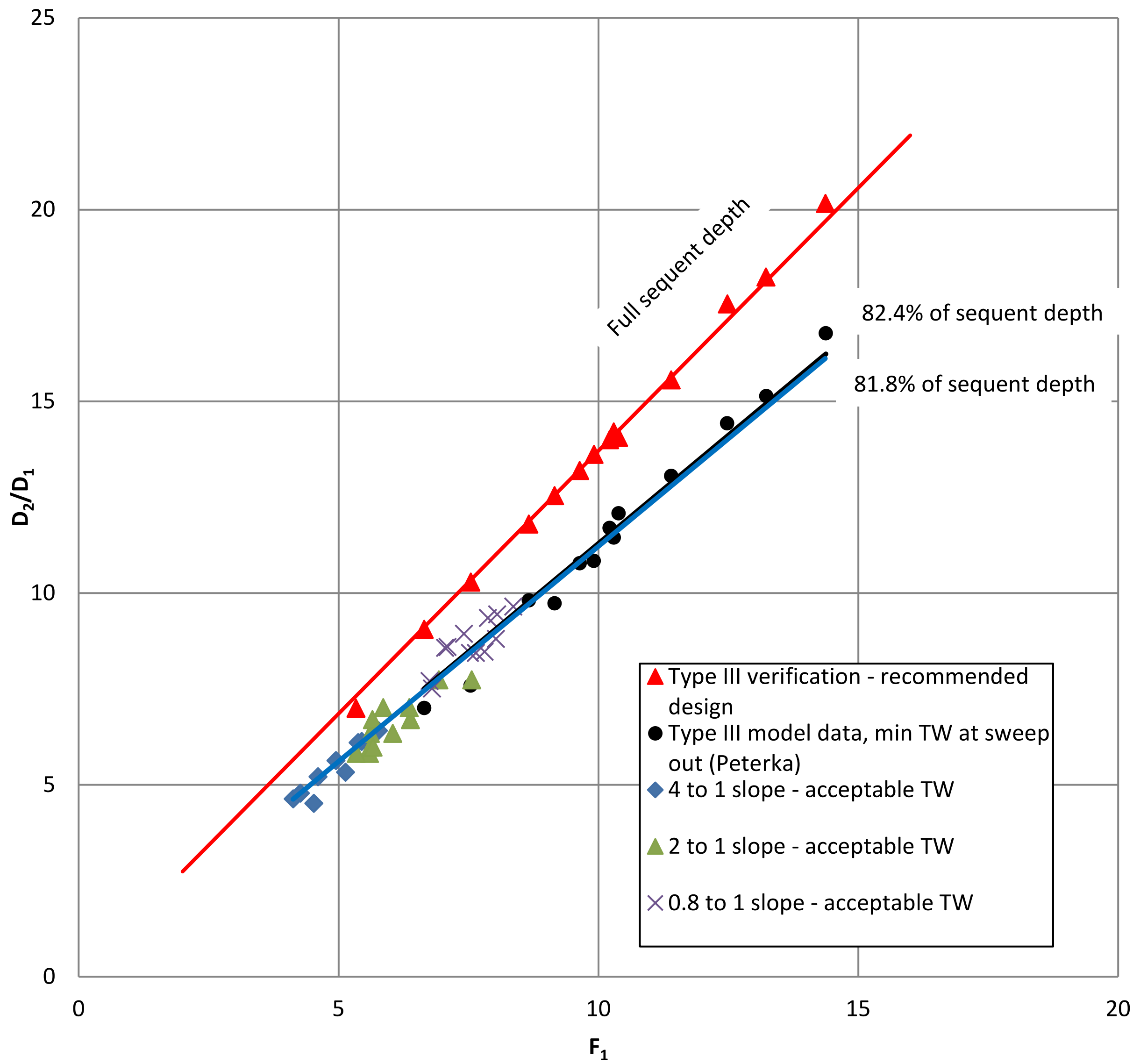

Figure 5. Stepped chute data with Type III (smooth) verification data from Peterka (1978) shown in red. Peterka's minimum tailwater (TW) data was 82.4-percent of sequent depth; Frizell and Svoboda (2012) data for all slopes are 81.8-percent of the sequent depth.

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.

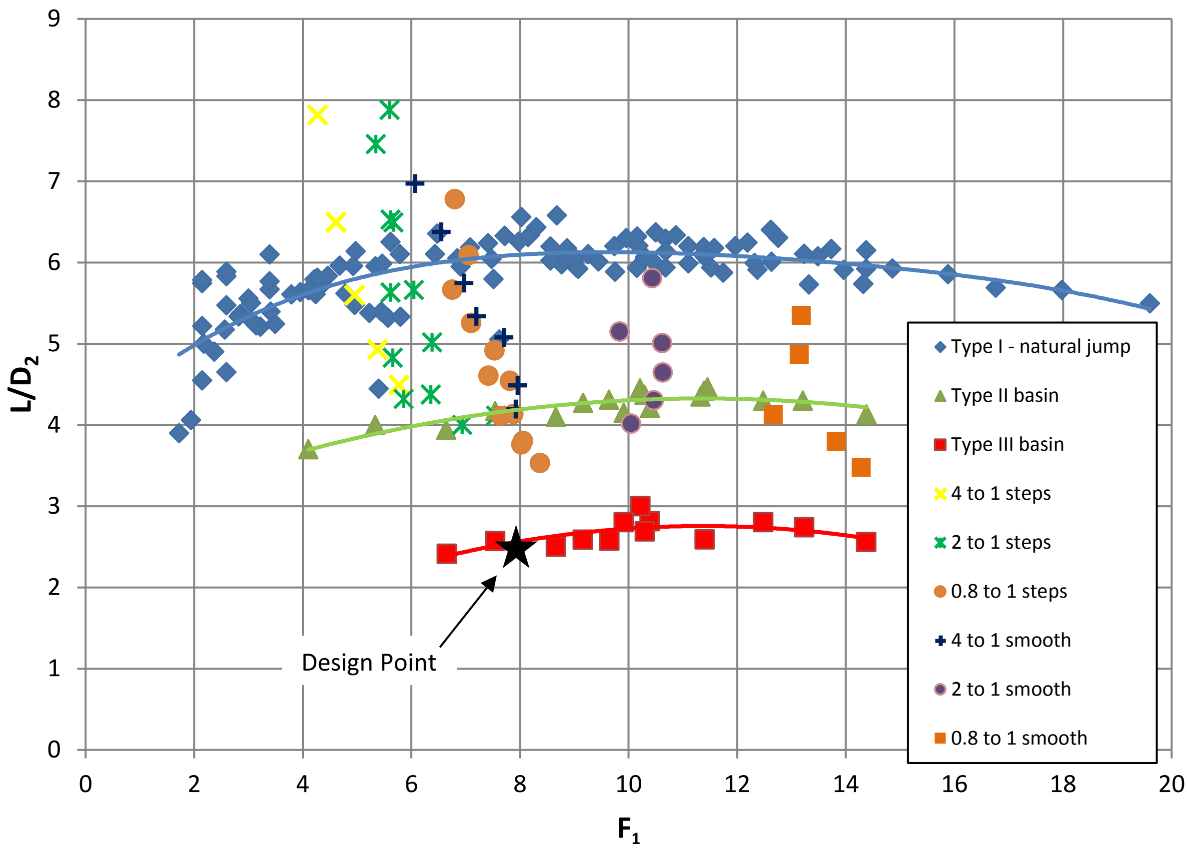

Figure 6. Stepped chute data plotted versus verification data for Type I, II, and Type III stilling basins, Peterka (1978). Model basin design point shown, F_1=8, D_1=76.2 mm, L_{iii}=2.159 m (from Peterka assuming full sequent depth).

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).

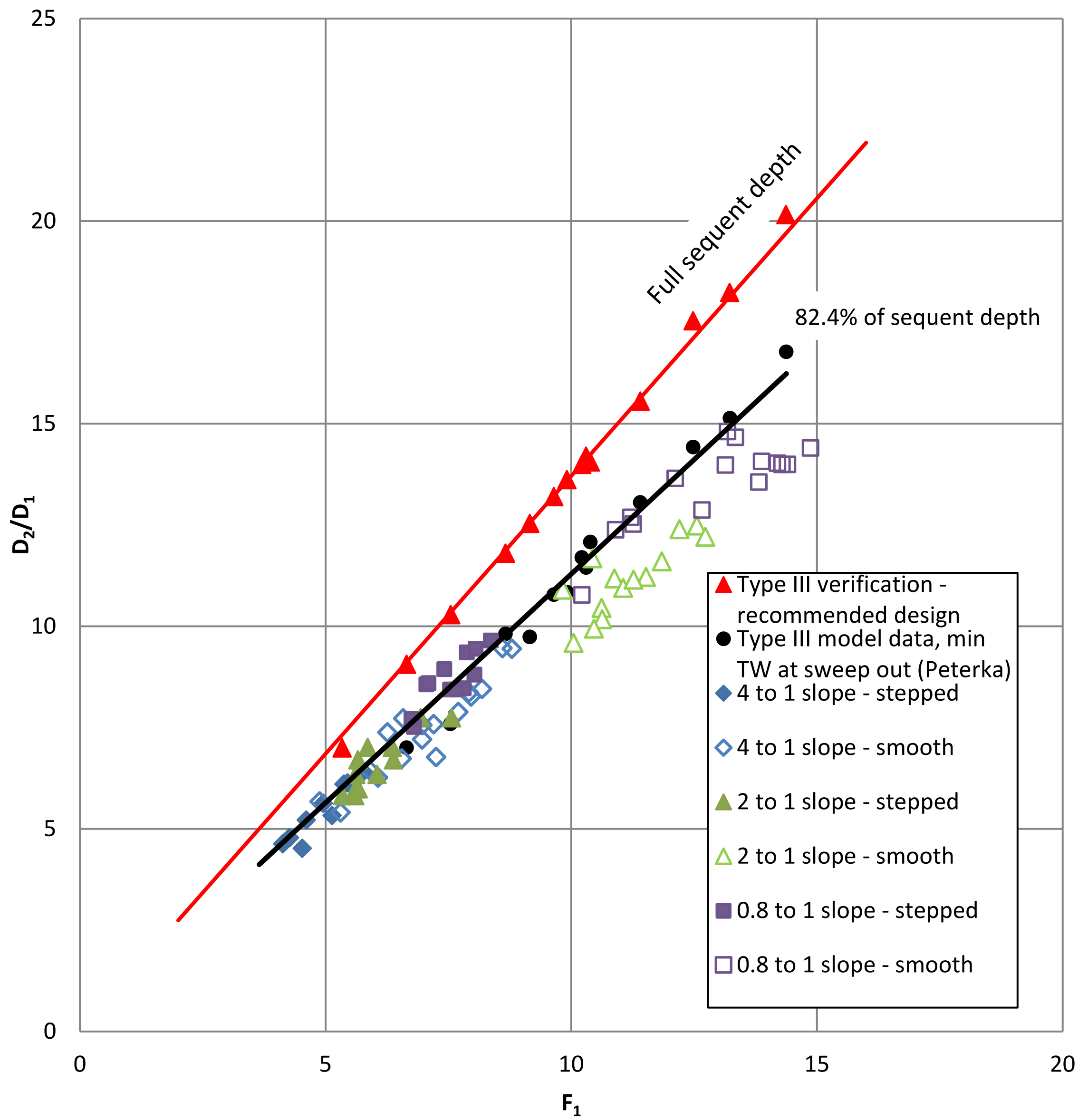

Figure 7. Smooth and stepped chute data from Frizell and Svoboda (2012), for all slopes; Type III (smooth) verification data from Peterka (1978) shown in red. Peterka's minimum tailwater (TW) data was 82.4-percent of sequent depth.

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

Boes, R.M. and Hager, W.H. (2003). "Hydraulic Design of Stepped Spillways." *J. Hyd. Engr*., American Society of Civil Engineers, 129(9), September, pp. 671-679.

Bradley, J.N. and Peterka, A.J. (1957a). "The Hydraulic Design of Stilling Basins: Hydraulic Jumps on a Horizontal Apron (Basin I)." *J. Hyd. Div*., Proceedings of the American Society of Civil Engineers, HY5, Paper 1401, October.

Bradley, J.N. and Peterka, A.J. (1957b). "The Hydraulic Design of Stilling Basins: High Dams, Earth Dams, and Large Canal Structures (Basin II)." *J. Hyd. Div*., Proceedings of the American Society of Civil Engineers, HY5, Paper 1402, October.

Bradley, J.N. and Peterka, A.J. (1957c). "The Hydraulic Design of Stilling Basins: Short Stilling Basin for Canal Structures, Small Outlet Works, and Small Spillways (Basin III)." *J. Hyd. Div*., Proceedings of the American Society of Civil Engineers, HY5, Paper 1403, October.

Bradley, J.N. and Peterka, A.J. (1957d). "The Hydraulic Design of Stilling Basins: Stilling Basin and Wave Suppressors for Canal Structures, Outlet Works, and Diversion Dams (Basin IV)." *J. Hyd. Div*., Proceedings of the American Society of Civil Engineers, HY5, Paper 1404, October.

Bradley, J.N. and Peterka, A.J. (1957e). "The Hydraulic Design of Stilling Basins: Stilling Basin with Sloping Apron (Basin V)." *J. Hyd. Div*., Proceedings of the American Society of Civil Engineers, HY5, Paper 1405, October.

Bradley, J.N. and Peterka, A.J. (1957f). "The Hydraulic Design of Stilling Basins: Small Basins for Pipe or Open Channel Outlets – No Tail Water Required (Basin VI)." *J. Hyd. Div*., Proceedings of the American Society of Civil Engineers, HY5, Paper 1406, October.

Bung, D.B. (2011). "Developing Flow in Skimming Flow Regime on Embankment Stepped Spillways." *Journal of Hydraulic Research*, 49(5), 639-648.

Bung, D.B., Sun, Q., Meireles, I., Viseu, T. and Matos, J. (2012). "USBR type III stilling basin performance for steep stepped spillways." *Proc., 4th IAHR International Symposium on Hydraulic Structures*, 9-11 February 2012, Porto, Portugal, ISBN: 978-989-8509-01-7.

Cardoso, G., Meireles, I. and Matos, J. (2007). "Pressure head along baffle stilling basins downstream of steeply sloping stepped chutes." *Proceedings 32nd IAHR Congress*, Venice, Italy (CD-ROM).

Chanson, H. (1994). *Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways*, Pergamon, Oxford, UK

Chanson, H. (2002). *The Hydraulics of Stepped Chutes and Spillways*. Balkema ed., ISBN 90 5809 352 2.

Chanson, H., Bung, D., and Matos, J. (2015). "Stepped spillways and cascades." In "Energy Dissipation in Hydraulic Structures." IAHR Monograph, CRC Press, Taylor & Francis Group, Leiden, The Nettherlands, H. Chanson Editor, pp. 45-64.

Frizell, K.H. (1990a). "Final Model Study Results for Milltown Hill Dam Spillway and Stilling Basin." United States Dept. of the Interior, Bureau of Reclamation, Internal Memorandum Water Resources Research Laboratory, August.

Frizell, K.H. (1990b). "Hydraulic Model Study of McClure Dam Existing and Proposed RCC Stepped Spillways." United States Dept. of the Interior, Bureau of Reclamation, R-90-02, Denver Colorado.

Frizell, K.H. (1992). “Hydraulics of Stepped Spillways for RCC Dams and Dam Rehabilitations,” *Proceedings of the American Society of Civil Engineers, Roller Compacted Concrete III Conference*, San Diego, CA, February.

Frizell, K.W. and Svoboda, C. (2012). “Performance of Type III Stilling Basins – Stepped Spillway Studies.” United States Dept. of the Interior, Bureau of Reclamation, HL-2012-02, Denver, Colorado.

Houston, K.L. (1987). “Hydraulic Model Studies of Upper Stillwater Dam Stepped Spillway and Outlet Works.” United States Dept. of the Interior, Bureau of Reclamation, REC-ERC-87-6, Denver Colorado.

Hunt, S. (2008). “Design of converging stepped spillways.” Ph.D. Dissertation, Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, Colorado.

Hunt, S. L. and Kadavy, K. C. (2014). “Flow depth and energy coefficient relationships for stepped spillways.” In: Hubert Chanson and Luke Toombes, Hydraulic structures and society - Engineering challenges and extremes. *5th IAHR International Symposium on Hydraulic Structures*, Brisbane, Australia, (1-9). 25-27 June 2014. doi:10.14264/uql.2014.25

Hunt, S., Kadavy, K., and Hanson, G. (2014). "Simplistic Design Methods for Moderate-Sloped Stepped Chutes." *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000938, 04014062.

Matos, J. (2000). “Hydraulic Design of Stepped Spillways over RCC Dams,” *Proc. Int. Workshop on Hydraulics of Stepped Spillways*,” VAW, ETH Zurich, Minor, H.E. and Hager, W.H. editors. Balkema, Rotterdam, pp. 187-194.

Meireles, I. and Matos, J.(2009). “Skimming flow in the non-aerated region of stepped spillways over embankment dams.” *J. Hydr. Eng*., ASCE, 135(8), pp. 865-869.

Meireles, I., Matos, J. and Silva-Afonso, A. (2010). “Flow characteristics along a USBR type III stilling basin downstream of steep stepped spillways.” *Proc. 3rd Int. Junior Researcher and Engineer Workshop on Hydraulic Structures*, Edinburgh, Scotland, Hydraulic Model Report CH80/10, The University of Queensland, Brisbane, Australia, pp. 57-64.

Meireles, I., Renna, F., Matos, J. and Bombardelli, F.A. (2012). “Skimming, Nonaerated Flow on Stepped Spillways over Roller Compacted Concrete Dams.” *Journal of Hydraulic Engineering*, 138(10), 870-877.

Peterka, A. J., (1978). “Hydraulic Design of Stilling Basins and Energy Dissipators.” United States Department of the Interior, Bureau of Reclamation, Engineering Monograph No. 25, Denver CO, 4th revised printing.

Pfister, M. and Hager, W.H. (2011). “Self-entrainment of Air on Stepped Spillways.” *International Journal of Multiphase Flow*, 37(2), 99-107.

Schwalt, M. and Hager, W.H. (1992). “Die Strahlbox (The jetbox).“ *Schweizer Ingenieur und Architekt* 110(27-28): 547-549 (in German).

Stephenson, D. (1991). “Energy Dissipation down Stepped Spillways.” *International Water Power and Dam Construction*, Vol. 43, September.

Takahashi, M., and Ohtsu, I. (2012). “Aerated Flow Characteristics of Skimming Flow over Stepped Chutes.” *Journal of Hydraulic Research*, 50(4), 427-434.