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Preliminary Results for Embankment Dam Stepped Spillway Stilling Basin Research

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Abstract: *A stilling basin is an energy dissipator for spillways and other hydraulic structures. Designed to generate a hydraulic jump, the structure is meant to contain the jump and return excess flow safely downstream. Traditional design for these structures was developed by United States Bureau of Reclamation (USBR) scientists. Tests were conducted for a range of expected flow conditions (e.g., Froude number, incoming flow depth, tailwater depth, etc.) with a smooth chute providing the incoming flow conditions. A common question among practicing engineers has become: is the stilling basin design criteria applicable if the approach entrance is a stepped chute? Scientists at the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) Hydraulic Engineering Research Unit (HERU) have developed a research program to evaluate the stilling basin performance associated with stepped chutes. Physical model tests are conducted in a near prototype scale stepped chute facility. Stilling basin Types I, II, III, and IV are being tested. Preliminary results indicate the Froude number at the stepped chute toe ranges from* $3.3 \leq F \leq 5.5$. *Hydraulic jumps within this Froude number range were observed to be oscillatory in nature and result in potentially undesirable wave action downstream of the stilling basin for the lower Froude numbers. Preliminary results indicate that the design criteria developed by USBR scientists are applicable for USBR Type IV stilling basins placed at the toe of stepped chutes. This research is expected to extend the knowledge base regarding stilling basins associated with stepped chutes.*

Keywords: *Stepped chutes, USBR stilling basin, hydraulic jump, energy dissipation, pressure, and Froude number.*

1. Introduction

Stepped chutes applied to embankment dams have become a common embankment overtopping protection system and method for increasing spillway capacity for aging embankment dams experiencing hazard creep. Hazard creep, is a term used to describe a hazard classification change of dams (e.g., low hazard to significant or high hazard or significant hazard to high hazard). Hazard creep normally occurs when dams have experienced changing demographics, such as increased infrastructure (e.g., residential communities, utilities, transportation systems, etc.) built in the downstream breach inundation zone. Stepped spillways provide advantages for addressing hazard creep situations. These advantages include (1) application to existing embankment dams, (2) significant energy dissipation, (3) cost savings and shorter construction schedules as compared to traditional reinforced concrete spillways, and (4) smaller footprint for the energy dissipation outlet works (e.g., stilling basin) (PCA 2002).

Extensive research on the hydraulic performance of stepped chutes applied to embankment dams is available. Table 1 provides a small sampling of literature on stepped chutes. Few studies (e.g., Meireles et al. (2005), Cardoso et al. (2007), Simões et al. (2010), Bung et al. (2012), Frizell and Svoboda (2012), Hunt et al. (2014), Frizell et al. (2016), and Valero et al. (2016)) have focused on the energy dissipation outlet works, specifically stilling basins, for stepped chutes. Stilling basins are a widely-accepted energy dissipation outlet works for smooth chute spillways. Bradley and Perterka (1957a-f) with the United States Bureau of Reclamation (USBR) conducted multiple studies on stilling basins that have varying design features: no dissipation blocks or end sill, end sill, floor blocks with an end sill, and floor blocks with a dentated end sill. Chanson (2002) identified prototype experience as one of the knowledge gaps in research for stepped chutes. In addition, the lack of data for the hydraulic performance of stilling basins for stepped chutes has also been identified as a knowledge gap in research. To address these knowledge gaps, scientists at the USDA-Agricultural Research Service (ARS) Hydraulic Engineering Research Unit (HERU) in Stillwater, Oklahoma, USA, have developed a research program to examine the performance of USBR stilling basins for stepped chutes in a nearby prototype modeling facility.

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Table 1. Summary of experimental conditions for stepped spillway research.

Reference[a]	θ (°)	B (m)	H_{crest} (m)	q ($m^3/(s{\cdot}m)$)	h (mm)	F*	h/d_c	R	W[b]	L/L_i
H-K (2013, 2017) H-K et al. (2014)	14 to 26.6	1.83	1.52 to 5.49	0.11 to 1.83	19 to 305	2.3 to 428	0.035 to 0.937	$3.1x10^4$ to $1.6x10^6$	$3.5x10^3$ to $1.9x10^5$	0.09 to 10.7
Boes (2000)	30	0.5	2.85	-	23.1, 46.2, 92.4	-	0.38 to 0.73	$3.1x10^4$ to $2.8x10^5$	$1.5x10^2$ to $1.7x10^4$	-
C-T (2002a)	3.4 to 4.0	0.5	1.48	0.04 to 0.164	Smooth to 143	0.97 to 10.4	0.54 to 1.08	$4.0x10^4$ to $1.64x10^5$	-	-
C-T (2002b)	15.9 to 21.8	1.0	1.1	0.04 to 0.26	100	0.74 to 5.32	0.53 to 1.82	$4.0x10^4$ to $2.6x10^5$	-	-
Ward (2002)	26.6	1.22	15.2	0.16 to 2.81	305, 710	0.55 to 7.8	0.37 to 2.17	$1.6x10^5$ to $2.8x10^6$	$7.2x10^3$ to $3.2x10^5$	-
Ohtsu et al. (2004)	5.7 to 55	0.4	0.45 to 2.47	0.016 to 0.093	6.25 to 100	-	0.03 to 1.21	$1.6x10^4$ to $9.3x10^4$	$4.8x10^2$ to $5.2x10^3$	-
C-C (2006)	22	1.0	1.0	0.095 to 0.18	100	-	0.63 to 1.03	$3.8x10^5$ to $7.1x10^5$	-	-
M-M (2009)	26.6	0.7	0.5	0.03 to 0.08	25, 50	1.5 to 11.2	0.35 to 0.79	$3.0x10^4$ to $8.0x10^4$	-	0.38 to 1.0
F-C (2008, 2013)	8.9 to 26.6	0.5	1.0	0.004 to 0.262	50 to 100	-	0.28 to 5.56	$3.1x10^4$ to $1.0x10^6$	-	-
Bung (2011)	18.4 to 26.6	0.3	2.34	0.07 to 0.11	30, 60	2.7 to 13.0	0.28 to 0.77	$2.3 x 10^5$	-	-

Note: [a]H-K (Hunt and Kadavy), C-T (Chanson and Toombes); C-C (Carosi and Chanson); M-M (Meireles and Matos), and F-C (Felder and Chanson). [b]Weber number based on the equivalent clear water flow depth as the reference length, L_s.

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1.1. Background

Bradley and Peterka (1957a-f) developed six types of stilling basins. The design criteria developed by Bradley and Peterka (1957a-f) was summarized in USBR (1973). While USDA-ARS HERU scientists are conducting research on USBR Type I, II, III, and IV stilling basins, the focus of this paper will be on the one of the most commonly designed stepped chute outlet works, the Type IV stilling basin. Fig. 1 provides a schematic of the Type IV stilling basin. According to USBR (1973), USBR Type IV stilling basins are recommended for $2.5 \leq F \leq 4.5$. The hydraulic jump occurring in a USBR Type IV stilling basin is described to be in the transitional stage such that the jump appears to be oscillatory in nature. To address the propagating waves generated from the oscillatory jump, the USBR Type IV stilling basin is a longer basin than a USBR Type III. An optional end sill and an increased tailwater depth for a USBR Type IV stilling basin as compared to the tailwater depth for a USBR Type III stilling basin keeps the hydraulic jump from sweeping out of the basin (USBR 1973).

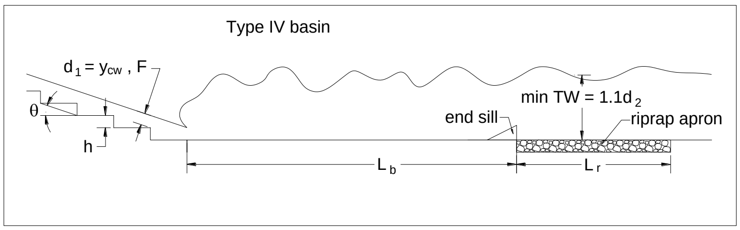

Figure 1. Schematic of an USBR Type IV stilling basin.

USBR (1973) outlines the design procedures for stilling basins and appurtenances (e.g., end sill, floor blocks, and chute blocks). Froude number (F), incoming clear water flow depth (e.g., $d_1 = y_{cw}$), sequent flow depth (d_2), and tailwater depth (TW) are the necessary design parameters for applying USBR stilling basin design procedures. Froude number is most commonly defined as

$$F = \frac{v}{\sqrt{g d_1}} \tag{1}$$

where v = velocity and g = gravitational constant. Hunt et al. (2014) indicated the Froude number may be rewritten in terms of the incoming clear water flow depth (i.e. $y_{cw} = d_1$) and the critical flow depth, d_c assuming continuity, such as the Froude number is

$$F = \left(\frac{y_{cw}}{d_c}\right)^{-1.5} \tag{2}$$

where $y_{cw} = d_1$ and $d_c = \left(\frac{q}{g^{0.5}}\right)^{2/3}$.

Hunt et al. (2014) provide prediction relationships for determining incoming clear water flow depth (e.g., $y_{cw} = d_1$) depending if the flow entering the stilling basin is upstream or downstream of the free surface inception point as outlined in Equations 3 and 4.

$$y_{cw} = 0.34\left(\frac{h}{d_c}\right)^{0.063} (\cos\theta)^{0.063} (\sin\theta)^{-0.18} d_c \qquad (L/L_i > 1.0) \tag{3}$$

$$y_{cw} = \left(\frac{L}{L_i}\right)^{-0.22} 0.34\left(\frac{h}{d_c}\right)^{0.063} (\cos\theta)^{0.063} (\sin\theta)^{-0.18} d_c \qquad (0.1 \leq L/L_i \leq 1.0) \tag{4}$$

where h = step height, θ = chute slope, L = length from the downstream edge of the broad-crested weir to the point of interest, and L_i = characteristic length from the downstream edge of the broad-crested weir to the free-surface inception point. The design criteria developed by Hunt et al. (2014) are valid for $10° \leq \theta \leq 30°$ and $h/d_c < 1/(1.2-0.325\tan\theta)$.

The sequent flow depth, d_2, as outlined by Bakhmeteff and Matzke (1936), who credit Bélanger, is

$$d_2 = \frac{1}{2}\left(\sqrt{1+8F^2}-1\right)d_1 \tag{5}$$

As shown in Fig. 1, USBR Type IV stilling basins have an optional end sill. The height of the end sill for a USBR Type IV stilling basin is approximately $1.25d_1$. To keep the hydraulic jump contained in an USBR Type IV stilling basin, the minimum tailwater (TW) is recommended to be a minimum of $1.1d_2$.

Meireles et al. (2005), Cardoso et al. (2007), Simões et al. (2010), Frizell and Svoboda (2012), Hunt et al. (2014), and Frizell et al. (2016) are a few of the researchers who have conducted comprehensive studies for expected Froude numbers for stilling basin design. Meireles et al. (2005) conducted tests on what appears to be a USBR Type I stilling basin as no floor blocks or end sill are identified in their set-up. The incoming approach to the stilling basin was a rather steep (i.e. $\theta = 53.1°$) stepped chute. Meireles et al. (2005) found that the pressure head on the stilling basin floor is approximately 4.4 times the critical flow depth. Cardoso et al. (2007) extended the research of Meireles et al. (2005) by investigating the pressure head in an USBR Type III stilling basin. Cardoso et al. (2007) concluded that the pressure head normalized by the critical flow depth (d_c) is independent of the step height on the approach chute and of the discharge. Cardoso et al. (2007) indicated that the USBR Type III stilling basin was approximately 20% shorter than the required length of a USBR Type I stilling basin. Simões et al. (2010) concentrated their studies on relatively steep ($45° \leq \theta \leq 59.04°$) stepped chutes. Froude numbers ranged from $4.01 \leq F \leq 11.6$ in their studies. It is unknown whether the studies were conducted for skimming flows or at what scales the tests were conducted. Studies by Frizell and Svoboda (2012) and Frizell et al. (2016) encompassed milder sloped ($14° \leq \theta \leq 51.34°$) stepped chutes that are indicative of those applied to embankment dams, where slopes typically range from $14° \leq \theta \leq 26.6°$. Frizell and Svoboda (2012) and Frizell et al. (2016) reported Froude numbers ranging from $4.0 \leq F \leq 14.8$. Froude numbers of this magnitude are typically associated with relatively high velocities, and in the case of Frizell and Svoboda (2012) and Frizell et al. (2016), the high velocities were induced by a jet box. A jet box may skew the results as the developing air entrained flow would not be developing naturally in the stepped chute. Hunt et al. (2014) solely focused their research on stepped chutes most commonly associated with embankment dams (i.e. $14° \leq \theta \leq 26.6°$). In addition, the research was conducted at near prototype conditions with reported Froude numbers ranging from $3.3 \leq F \leq 5.5$. Unlike Frizell and Svoboda (2012) and Frizell et al. (2016), Hunt et al. (2014) allowed the air entrained flow to develop naturally as one would expect in a real-world application of a stepped chute. Frizell et al. (2016) concluded the Bradley and Perterka (1957a-f) design criteria for stilling basins can be confidently applied to stepped chutes; however, given the high velocities and subsequent Froude numbers reported from their study, it appears appropriate to investigate the application of stilling basins associated with stepped chutes a bit further. In addition, today's technology allows for a more comprehensive data collection (e.g., floor pressures, air concentrations, velocities) than originally reported by Bradley and Peterka (1957a-f). Thus, this study is intended to extend the knowledge base for stilling basin design.

2. Experimental Set-Up

Scientists at the USDA-ARS HERU are in the preliminary stages of conducting research on a series of stilling basin types (e.g., USBR Type I, II, III, and IV) first established by Bradley and Peterka (1957a-f) and outlined in USBR (1973). The stilling basin approach for all tests is a large-scale 3(H):1(V) (e.g., $\theta = 18.4°$) stepped chute with a width of 1.83 m, total drop of 5.18 m, and step height of 305 mm. This stepped chute facility was designed and constructed to minimize scale effects as described by Hunt et al. (2014). To date, the USBR Type IV stilling basin with a width of 1.83 m has been tested with discharges of 0.42, 0.85, and 1.7 m^3/s. These discharges are classified as skimming flow according to Chanson (2002) and Ohstu et al. (2004). The stilling basin length, end sill height, and tailwater were adjusted for each test depending on discharge according to USBR (1973) criteria. Based on the discharges of 0.42, 0.85, and 1.7 m^3/s, the measured Froude number was 4.56, 4.22, and 4.10, respectively, as compared to the calculated Froude numbers of 3.77, 3.93, and 4.11 using Eq. (1). The stilling basin proportions were designed using the calculated Froude numbers, thus resulting in stilling basin lengths (L_{basin}) tested of 2.0, 3.3, and 5.4 m and end sill height ($h_{endsill}$) of 0.09, 0.14, and 0.22 m, respectively. During testing, the measured flow depth and velocity at the entrance to the stilling basin was used to calculate the Froude number and sequent flow depth (d_2). The sequent flow depth was also measured during the tests. These measured data were used to set the tailwater for each test and used for the data analysis reported herein. Fig. 2 illustrates an USBR Type IV stilling basin in relation to the end sill configurations.

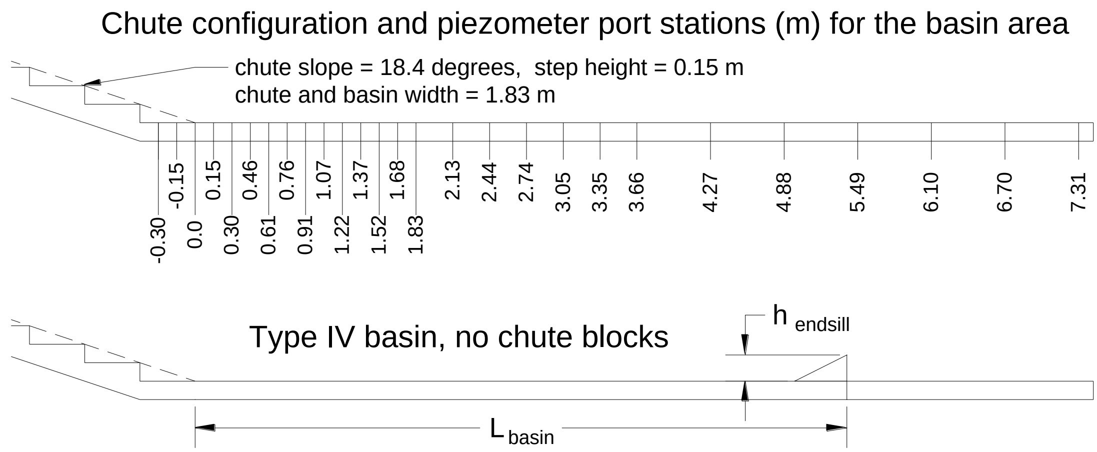

Figure 2. Schematics of (a) the piezometer port locations for obtaining pressure readings along the centerline of the stilling basin floor and (b) the USBR Type IV stilling basin test configuration.

Data collected during each test included water surface elevation, bed surface elevation, flow depth, pressure head, velocity, and air concentration. A two-tipped fiber optic probe coupled with a data acquisition system served as the instrumentation for flow depth, velocity, and air concentration measurements on the chute at the entrance to the stilling basin. In the stilling basin area, a point gage was used to measure water surface and bed surface elevations. Pressure measurements from up to twenty-seven piezometer port stations along the centerline of the stilling basin floor were collected. Fig. 2 illustrates the chute configuration and the piezometer port stations for the USBR Type IV stilling basin. These readings were taken both visually from a manometer board coupled with a pressure transducer manifold as well as electronically with a data acquisition system. The pressure transducer system was an UltraLow Wet-Wet differential pressure transducer (e.g., Validyne DP DP103) connected to a sine wave carrier demodulator (e.g., Validyne CD15). The high-pressure port was connected to the piezometer manifold and the low-pressure port open to the atmosphere. The demodulator output was +/-10 Vdc, and the accuracy was +/- 0.25% FS (+/- 5.6 mm). The data acquisition system was a DataQ DI-158U compact data acquisition kit with a 12-bit resolution. It had a range of +/- 10V, an accuracy of +/- 0.25% FSR, a resolution of +/- 4.88 mV, a sampling rate of 100 HZ, and a sampling time of 60 seconds.

3. Discussion and Conclusions

For stilling basins, Hunt et al. (2014) reported incoming Froude numbers of $3.3 \leq F \leq 5.5$ with stepped chutes approach conditions. The percent difference in the measured and calculated ranged from 0.2% to 17%, with the greatest difference observed for a test discharge of 0.42 m^3/s. While the tests were conducted under skimming flow conditions according to Chanson (2002) and Ohstu et al. (2004), visual observations during tests noted the discharge of 0.42 m^3/s was very close to the nappe or transitional flow regime. This observation may account for the greatest difference between the measured and calculated Froude number for the smallest discharge tested. Unlike Frizell et al. (2012), these Froude numbers were generated by the aerated flow developing naturally as it descended the chute. For the lower Froude numbers, an oscillatory hydraulic jump was observed, which is indicative of Froude numbers within a range of $2.5 \leq F \leq 4.5$ according to USBR (1973). With the oscillatory jump, waves were observed to propagate downstream of the stilling basin when the optional end sill was not included in the design. When tested with the optional end sill, the oscillatory wave action was dampened to some degree. For $F > 4.0$, the hydraulic jump becomes better well-balanced. Increasing the tailwater above the recommended tailwater setting appears to dampen the oscillating behavior of the jump, but the improvement is slight.

The pressure data was used to determine the pressure head, H_p, and, along with the other elevation data, was referenced to the stilling basin floor elevation of 0.0 m. Fig. 3 illustrates the maximum, mean, and minimum pressure heads; the variance of the pressure data; the pressure head from the manometer board data; and the water surface elevations observed for the USBR Type IV stilling basin at a discharge of 1.7 m^3/s. The pressure head at all locations along the stilling basin floor were positive which reduces the potential uplift forces on the basin floor slab. The maximum pressure head occurs near the intersection of the pseudo-bottom of the chute floor and the stilling basin floor or approximately station 0 m, while the minimum pressure head occurs slightly upstream of station 0 m near the step edge of the chute. The water surface elevations correspond with the mean pressure head as the flow approaches the stilling basin end sill. The mean pressure head from the pressure transducer data and the manometer board data agree with one another. The variance (σ^2) of the pressure data was used as an indicator of the turbulence level along the length of the basin. The flow turbulence slowly decays along the length of the basin and reaches minimum values near the end sill. The data for the stilling basins tested at a discharge of 0.42 and 0.85 m^3/s showed similar trends.

To generalize the data the mean pressure head, water surface elevation and bed surface elevation data were normalized by the sequent flow depth (d_2). Fig. 4 illustrates the normalized water surface elevation as the normalized mean pressure head approaches the design normalized tailwater elevation of $1.1d_2$ near the location of the endsill, and the length of the hydraulic jump is between $5d_2$ to $6d_2$ from the toe of the stepped chute. The length of the hydraulic jump is in good agreement with Bradley and Peterka (1957d) and USBR (1973).

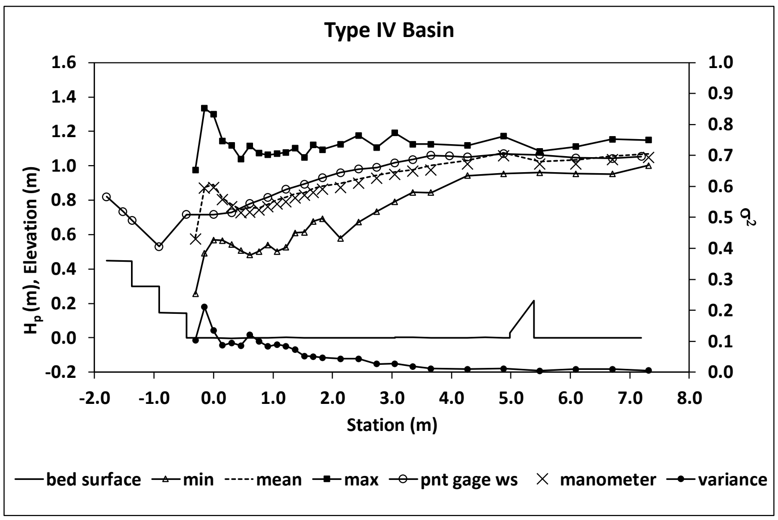

Figure 3. Maximum, minimum, and mean pressure head (H_p); manometer pressure head; water surface elevations; bed surface elevations; and variance of pressure data along the centerline of an USBR Type IV stilling basin tested with a discharge of 1.7 m^3/s.

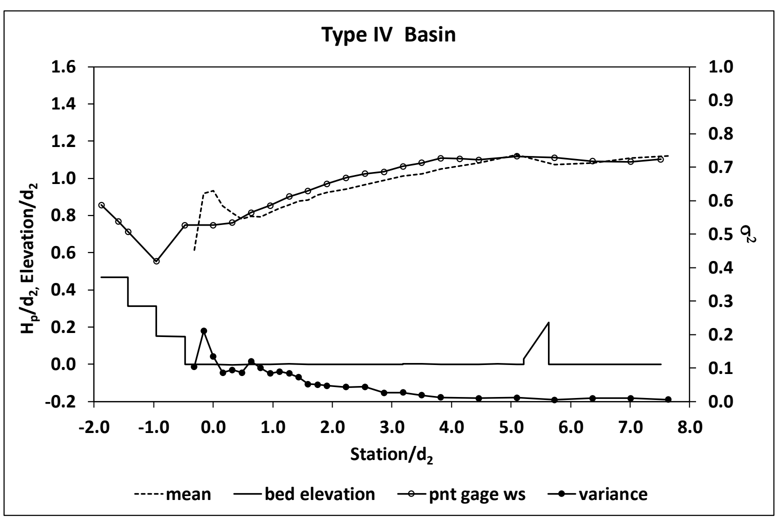

Figure 4. Mean pressure head, H_p, and water surface elevation normalized by the sequent flow depth, d_2, along the centerline of an USBR Type IV stilling basin tested with a discharge of 1.7 m^3/s.

The preliminary results provided herein extend the knowledge on stilling basin performance when designed as the outlet works for stepped chutes. The research performed by Bradley and Peterka (1957a-f) provide a basis for designing stilling basins for stepped chutes. The results from this research indicate that the stilling basin design criteria developed by Bradley and Peterka (1957d) and summarized by USBR (1973) is applicable for stepped chutes. In addition, these preliminary results may alleviate design engineers' concerns of negative pressures underneath the stilling basin floor.

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5. References

Bakhmeteff, B.A., and Matzke, A.E. (1936). "The hydraulic jump in terms of dynamic similarity." *Proc. of the American Society of Civil Engineers, Transactions 101,* 62(8 Part 2), 630-647.

Boes, R.M. (2000). "Scale effects in modeling two-phase stepped spillway flow." *Intl. Workshop on Hydraulics of Stepped Spillways,* Zürich, Switzerland, H.E. Minor and W.H. Hager Editors, Balkema Publ., 53-60.

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., *Proc. of the American Society of Civil Engineers*, HY5, Paper 1401. Ann Arbor, MI: ASCE.

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., *Proc. of the American Society of Civil Engineers*, HY5, Paper 1402. Ann Arbor, MI: ASCE.

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., *Proc. of the American Society of Civil Engineers*, HY5, Paper 1403. Ann Arbor, MI: ASCE.

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., *Proc. of the American Society of Civil Engineers*, HY5, Paper 1404. Ann Arbor, MI: ASCE.

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

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., *Proc. of the American Society of Civil Engineers*, HY5, Paper 1406. Ann Arbor, MI: ASCE.

Bung, D.B. (2011). "Developing flow in skimming flow regime on embankment stepped spillways." *J. of Hyd. Research*, 49(5), 639-648.

Bung, D.B., Sun, Q., Meireles, I., Matos, J., and Viseu, T. (2012). "USBR type III stilling basin performance for steep stepped spillways." *Proc.* 4th *IAHR International Symposium on Hydraulic Structures*, Porto, Portugal.

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

Carosi, G., and Chanson, H. (2006). "Air-water time and length scales in skimming flows on a stepped spillway. Aapplication to the spray characterisation." *Report No. CH59/06,* Div. of Civil Engineering, The University of Queensland, Brisbane, Australia.

Chanson, H. (2002). *The Hydraulics of Stepped Chutes and Spillways.* Steenwijk, The Netherlands: A.A. Balkema Publishers.

Chanson, H., and Toombes, L. (2002a). "Experimental investigations of air entrainment in transition and skimming flows down a step chute." *Can. J. Civ. Eng.,* 29(1), 145-156.

Chanson, H., and Toombes, L. (2002b). "Energy dissipation and air entrainment in a stepped storm waterway: An experimental study." *J. Irrig. and Dra. Eng.*, ASCE, 128(5), 305-315.

Felder, S., and Chanson, H. (2008). “Turbulence and turbulent length and time scales in skimming flows on a stepped spillway.” Dynamic Similarity, Physical Modelling and Scale Effects. Report No. CH64/07, Hydraulic Model Report CH series, Division of Civil Engineering, The University of Queensland, Brisbane, Australia.

Felder, S., and Chanson, H. (2013). “Aeration, flow instabilities, and residual energy on pooled stepped spillways of embankment dams.” *J. Irrig. and Dra. Eng.*, ASCE, 139(10), 880-887.

Frizell, K.W., and Svoboda, C.D. (2012). “Performance of type III stilling basins—stepped spillway studies—do stepped spillways affect traditional design parameters?” United States Dept. of the Interior, Bureau of Reclamation, Hydraulic Laboratory Report HL-2012-02, Denver, CO.

Frizell, K.W., Svoboda, C., and Matos, J. (2016). “Performance of type III stilling basins for stepped spillways.” *Proc. Protections 2016: 2nd International Seminar on Dam Protection Against Overtopping*. Ft. Collins, CO.

Hunt, S.L., and Kadavy, K.C. (2013). “Inception point for embankment dam stepped spillways.” *J. Hyd. Eng., ASCE*, 139(1), 60-64.

Hunt, S.L., Kadavy, K.C., and Hanson, G.J. (2014). “Simplistic design methods for moderate-sloped stepped chutes.” *J. Hyd. Eng.,* ASCE.

Hunt, S. L., and Kadvay, K.C. (2017). “Estimated splash and training wall height requirements for stepped chutes applied to embankment dams.” *J. Hyd. Eng.*, ASCE.

Meireles, I., and Matos, J. (2009). “Skimming flow in the nonaerated region of stepped spillways over embankment dams.” *J. Hyd. Eng.,* ASCE, 135(8), 685-689.

Meireles, I., Matos, J., and Falcão Del Melo, J. (2005). “Pressure head and residual energy in skimming flow on steeply sloping stepped spillways.” *Proc. of 31st IAHR Congress*, IAHR, Seoul, Korea, 2654-2663.

Ohtsu, I., Yasuda, Y., and Takahashi, M. (2004). “Flow characteristics of skimming flows in stepped channels.” *J. Hyd. Eng.*, 130(9), 860-869.

Portland Cement Association (PCA). (2002). *Design manual for RCC spillways and overtopping protection.* Portland Cement Association, Skokie, IL.

Simões, A.L.A, Schulz, H.E., and Porto, R.D. (2010). “Stepped and smooth spillways: resistance effects on stilling basin lengths.” *J. Hyd. Res.* 48(3), 329-337.

United States of the Interior Bureau of Reclamation (USBR). (1973). *Design of Small Dams.* U.S. Government Printing Office, Denver, CO.

Valero, D., Bung, D.B., Crookston, B., and Matos, J. (2016). “Numerical investigation of USBR type III stilling basin performance downstream of smooth and stepped spillways.” *Proc. 6th IAHR International Symposium on Hydraulic Structures,* Portland, Oregon.

Ward, J. (2002). “Hydraulic design of stepped spillways.” PHD Dissertation. Colorado State University, Ft. Collins, CO.