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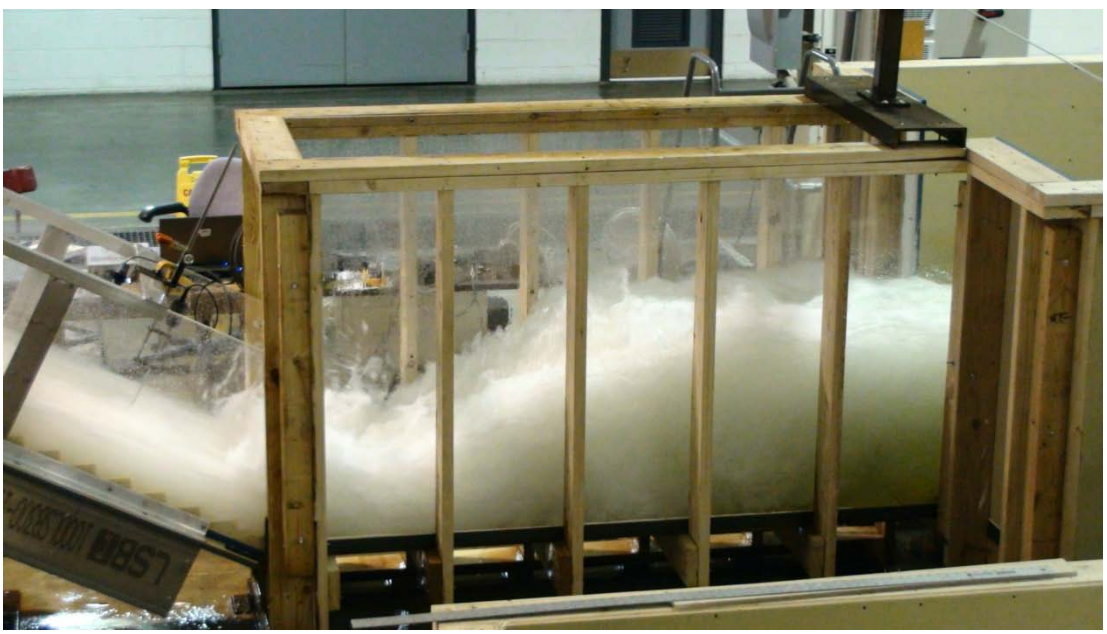
**Hydraulic Laboratory Report HL-2012-02**

# Performance of Type III Stilling Basins – Stepped Spillway Studies

## Do Stepped Spillways Affect Traditional Design Parameters?



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**14. ABSTRACT**
This report summarizes laboratory studies carried out in a section flume model capable of slopes of 14.04-, 26.57-, and 51.34-degrees above the horizontal with either smooth of stepped inverts. The spillway terminated in a Reclamation type III stilling basin designed for an incoming Froude number of 8 with an initial depth of 76.2 mm (0.25 ft). Data were collected for a variety of flow rates at each slope and invert type. Tailwater required for acceptable basin performance, incoming flow depth, and discharge were measured for each case. Data were compared with design charts published in Reclamation's Engineering Monograph No. 25. New data representing stilling basin performance with stepped spillways is included. In addition, the benefit of using a newly designed supercavitating baffle block was demonstrated by showing the between 6 to 12 percent less tailwater is required for satisfactory stilling basin performance than with the existing standard baffle block design.

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stepped spillways, type III stilling basin, supercavitating baffle block, jet box

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# Performance of Type III Stilling Basins – Stepped Spillway Studies

## Do Stepped Spillways Affect Traditional Design Parameters?


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Denver, Colorado

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.


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## Hydraulic Laboratory Reports

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Cover Photo: Hydraulic model in Reclamation's laboratory showing a stepped chute at a slope of 26.57-degrees (2H:1V) terminating in a Type III stilling basin.


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# CONTENTS



# TABLES



# FIGURES

# LIST OF SYMBOLS

$C_a$ – actual air concentration
$C_m$ – mean air concentration (average over a vertical profile)
$C_{meas}$ – air concentration measured with bubble detector
$D$ – depth
$D_1$ – incoming depth to stilling basin
$D_2$ – depth at end of basin (tailwater)
$D_{cw}$ – clear water depth calculated using mean air concentration
$D_{90}$ – depth where air concentration is 90-percent air
$F_1$ – Froude number at beginning of stilling basin
$g$ – gravitational constant (32.2 ft/s$^2$)
$q$ – specific discharge (discharge per unit width)
$Q$ – total discharge
$V$ – velocity
$V_1$ – velocity at beginning of stilling basin
$V_2$ – velocity downstream of hydraulic jump
$V_m$ – mean velocity ($Q/D$)

# Introduction

In the late 1950's Bureau of Reclamation (Reclamation) personnel (Bradley & Peterka, 1957) 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.

The stilling basins that will be addressed in this document 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, the hydraulic jump can be expressed as:

$$D_2 = -\frac{D_1}{2} + \sqrt{\frac{D_1^2}{4} + \frac{2V_1^2 D_1^2}{gD_1}} \qquad \text{Eq. 1}$$

Where $D_1$ and $D_2$ are the sequent depths, $V_1$ is the velocity at section 1 and $g$ is the gravitational constant. Rearranging this expression and defining the ratio of inertial to gravitational forces as $\sqrt{V}/gD$ (commonly known as the Froude Number), we can show that the ratio of sequent depths in a hydraulic jump is a linear function of incoming Froude Number:

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

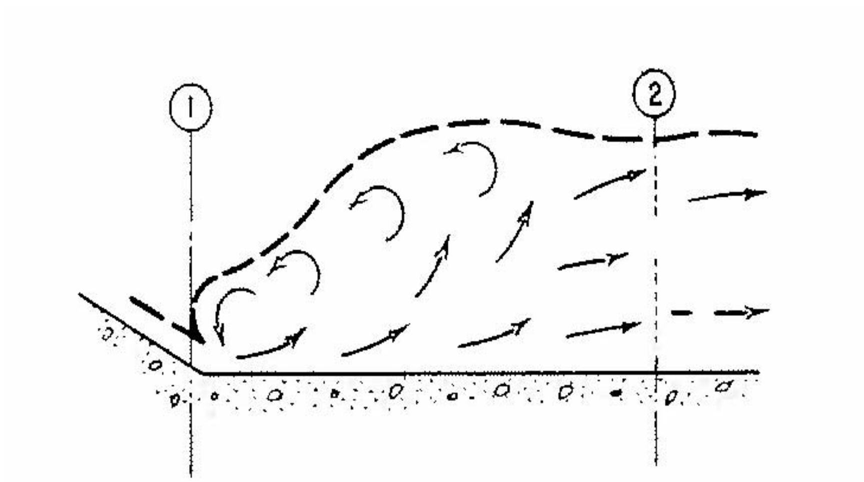


**Figure 1.** Design parameters for stilling basins include velocity ($V_1$) and depth ($D_1$) at section 1 before the hydraulic jump and velocity ($V_2$) and depth ($D_2$) at section 2 after the hydraulic jump.

Included in Monograph No. 25 is a chapter on Reclamation's Type III stilling basin. The general application was for a short stilling basin on canal structures, small outlet works, and small spillways, figure 2. Identical to the Type II basin except for the addition of a row of baffle piers along the floor of the basin, the additional energy dissipation allowed for a considerably shortened 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.

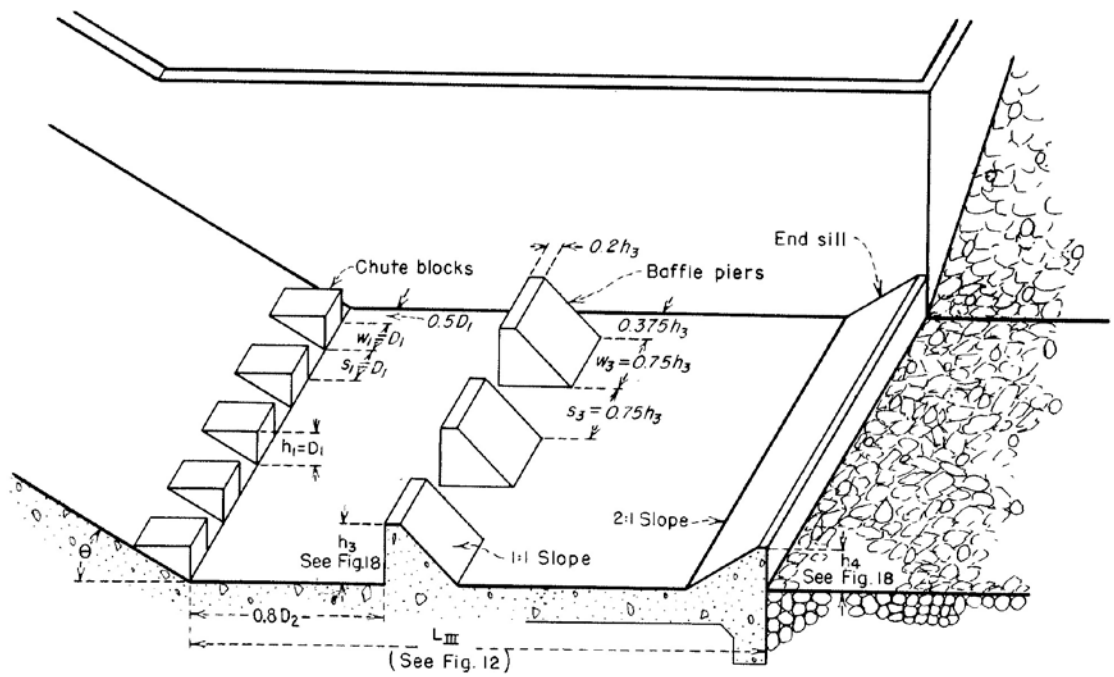


**Figure 2.** Layout of Reclamation Type III stilling basin (Peterka, 1978).

Over the years, there have been many questions about the type III basin. Most have been concerned with high velocity flows and possible damage to the baffle piers or the stilling basin floor due to cavitation or erosion by sediment-laden flows. The project that spurred the current investigation was the modeling of the new auxiliary spillway for Folsom Dam, near Sacramento, California. This new design featured many novel design characteristics including: transition from a high-velocity smooth spillway chute to a stepped spillway, and a modified type III basin with a design specific discharge of $q$=70 m$^2$/s (754 ft$^2$/s) and maximum specific discharge of $q$=163 m$^2$/s (1755 ft$^2$/s). These design parameters are not only outside the guidance for the type III basin but also those for a typical stepped spillway. Results from a 1:26 scale model of the Folsom auxiliary spillway at St. Anthony Falls Laboratory, considerably lengthened the stilling basin from an initial design based on predictions that attempted to include the influence of flow over the steps, Lueker, et.al. (2008).

During studies at Reclamation's hydraulics laboratory, Frizell (2009) modified the standard baffle block shape to a design that was more favorable regarding possible cavitation damage with the extremely high velocity flows in the range of 25-37 m/s (82-121 ft/s) entering the basin. During modeling that included this new baffle design, Svoboda et.al. (2010) found that the basin performed well at significantly lower tailwater elevations than the standard design baffle block. This discovery along with the studies that led to the initial lengthening of the basin brought up questions about how the enhanced energy dissipation that occurs on a stepped spillway affects the performance of the stilling basin. In particular, what are the effects of a decreased mean velocity, a modified vertical velocity profile, increased depth due to bulking and possibly other effects of the complex aerated flow? Or was the result specific to the new block design and floor ramps or other geometric properties of the stilling basin (e.g. width or modified design dimensions)?

Many researchers have studied the enhanced energy dissipation on stepped chutes operating in the skimming flow regime Stephenson (1991), Chanson (1994, 2002), Matos (2000), Boes and Hager (2003), Meireles and Matos (2009). 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) and Meireles (2011) studied particular features of type III basins at the terminus of stepped chutes. The main findings of these studies were that the pressure head (depth or $D_2$) near the end of the jump was 20-percent less for the Type III basin versus a Type I basin (horizontal apron with no features), and that the length of the hydraulic jump was also reduced to 80-percent of that for the Type I basin.

The present study compared Type III stilling basin performance for smooth and stepped chutes on three slopes for a range of discharges. In particular, whether current design guidance for type III basins can be applied to stepped chutes preceding the stilling basin and what, if any, corrections or modifications are needed.

## Experimental Setup

The studies were completed at Reclamation's Hydraulics Laboratory, located in Denver, Colorado. A new flume was constructed, allowing the sectional (in width) representation of a spillway chute and type III stilling basin, figure 3. The main features of the model included a flume of adjustable slope, a pressurized *jet box* (Schwalt, M. and Hager, W.H. 1992), a standard type III stilling basin 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. 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).

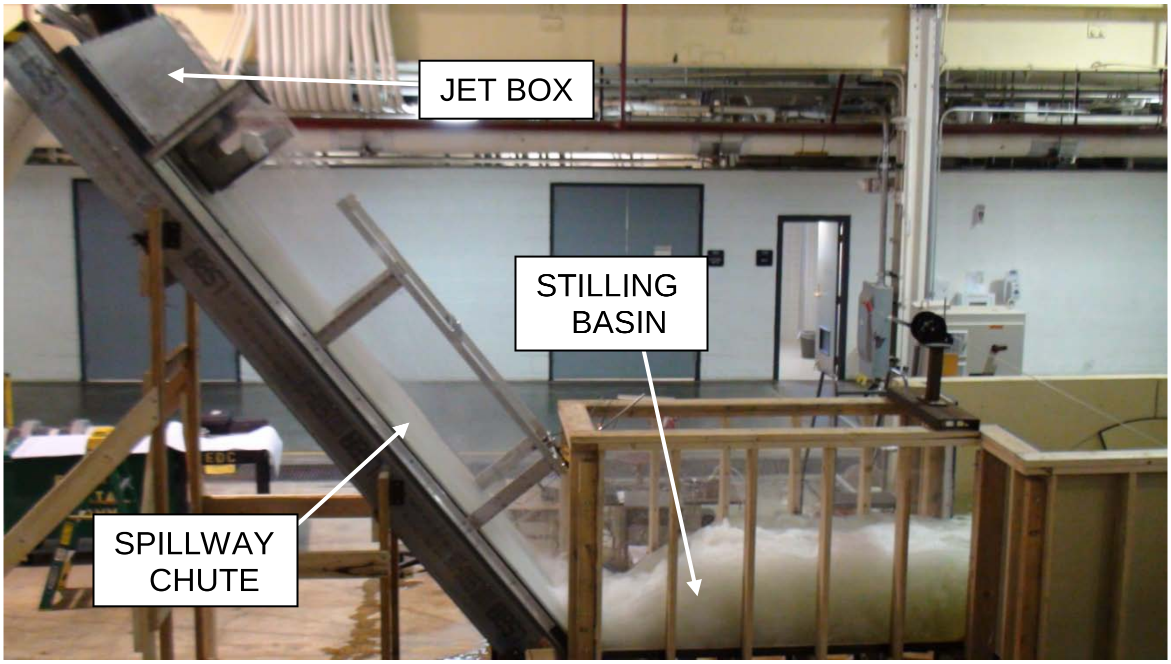

**Figure 3:** Stilling basin model with a smooth chute at a slope of 53.1-degrees.

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 $ft^2/s$). Uniform flow conditions were attained towards the downstream end of the chute and verified by comparing air concentration profiles at the chute end with a cross section further upstream with good agreement. In addition, measured mean air concentrations were compared to computed uniform depth-averaged air concentrations for smooth chutes and were found to be generally within 20-percent.

## Methods

Discharges to the model were measured and controlled with the laboratory supply system. Flow rates were determined using a venturi meter calibrated to an accuracy of ±0.5-percent of discharge reading. Other important parameters that were measured included the incoming depth to the stilling basin, $D_1$, the depth exiting the stilling basin, $D_2$, and air concentration profiles on the spillway near the entrance to the stilling basin. The incoming depth was determined in two ways: 1. Direct measurement with an ultrasonic water level sensor (figure 4) and 2. Measuring the air concentration profile to determine the depth where the air concentration was 90-percent. The ultrasonic sensor was manufactured by MassaSonic™ and was Model M-5000/220, capable of a resolution of 0.3 mm ($9.8 \times 10^{-4}$ ft). The air-concentrations were measured using a dual-tipped bubble detection probe (figure 5) designed and built at Reclamation's hydraulics laboratory (Frizell et. al., 1994). The calibration of the probe is mainly dependent on probe tip geometry and matching operational settings, such as the balance point when collecting data. Calibration of an identical probe was carried out at the Instituto Superior Technico (IST) of the

Technical University of Lisbon in Portugal, yielding a best-fit calibration curve given by equation 3

$$C_a = 0.1105C_{meas}^3 + 0.8814\sqrt{C_{meas}} \qquad \text{Eq. 3}$$

where $C_a$ is the actual air concentration and $C_{meas}$ is the measured value from the meter. The probe output was recorded using a laptop computer and IOTech PersonalDaq 3005 data acquisition system. Data records at each vertical location were collected for 60 s at a sample rate of 1500 Hz and then integrated over time to provide the air concentration at that position. Mean air concentrations were determined by numerical integration of the vertical air concentration profile from the invert or virtual boundary (stepped chute) up to the point where the air concentration was 90-percent. Once the mean air concentration ($C_m$) had been determined, the effective clear-water depth ($D_{cw}$) for a uniform flow could be computed using equation 4.

$$D_{cw} = (1 - C_m)D_{90} \qquad \text{Eq. 4}$$

The clear-water depth and the average velocity $V_m = Q/D_{90}$ were then used to calculate the incoming Froude number, $F_1 = V_m/\sqrt{gD_{cw}}$, where $g$ is the gravitational constant. The tailwater, adjusted by the flap gate at the exit of the tailbox was measured in a stilling well, just downstream from the exit of the stilling basin in the expanded tailbox. A vertical hook gage was used to read the water level in the stilling well to an accuracy of ±0.3 mm ($9.8 \times 10^{-4}$ ft).

## Testing

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, measuring a vertical air concentration profile on the chute near the basin entrance to find the mean air concentration, calculating the effective $D_1$, and reading the stilling well to determine $D_2$. 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. On occasion velocity profiles were collected with a pitot-static tube at the same location as the air concentration profile (this was done only for those conditions for which aeration did not interfere with the measurements).

**Figure 4:** MassaSonic™ ultrasonic distance probe.

**Figure 5:** Dual tipped bubble detector and conductivity probe for air concentration measurements.

## Results

Three channel slopes were tested with both smooth and stepped chutes, terminating in the same type III stilling basin. The major results are presented in Table 1.

For the stepped chute, tailwater elevations were also decreased to the point of sweep out (i.e., condition for which the toe of the jump moves onto the horizontal surface of the stilling basin floor). Figure 6 shows the position of the toe of the hydraulic jump with both smooth and stepped chutes for standard operation and sweep out. While the onset of sweep out may not be a critical or dangerous situation, sweep out does produce higher velocities within the basin. Excessive splashing and jetting can occur from impact on the baffle blocks. The tailwater can become unstable, exacerbating the poor conditions and dramatically increasing the velocities exiting the stilling basin to the point of causing damage to the downstream channel and even possibly undermining of the structure itself.

**Table 1:** Data from laboratory experiments for all slopes and smooth and stepped chutes.

| $Q$ ($m^3/s$) | $D_1$ (mm) | $C_m$ | $F_1$ | $D_2$ (mm) | $D_2/D_1$ | Slope (deg) | Chute Type |
|---|---|---|---|---|---|---|---|
| 0.127 | 49.4 | | 6.07 | 309.7 | 6.27 | 14.04 | smooth |
| 0.141 | 50.3 | | 6.55 | 338.6 | 6.73 | 14.04 | smooth |
| 0.158 | 52.1 | | 6.97 | 375.8 | 7.21 | 14.04 | smooth |
| 0.169 | 53.3 | | 7.20 | 404.5 | 7.58 | 14.04 | smooth |
| 0.184 | 53.9 | | 7.70 | 425.2 | 7.88 | 14.04 | smooth |
| 0.214 | 58.2 | | 7.96 | 481.3 | 8.27 | 14.04 | smooth |
| 0.231 | 61.6 | | 7.92 | 514.8 | 8.36 | 14.04 | smooth |
| 0.115 | 53.0 | | 4.94 | 301.1 | 5.68 | 14.04 | smooth |
| 0.170 | 61.0 | | 5.91 | 392.0 | 6.43 | 14.04 | smooth |
| 0.232 | 60.4 | | 8.18 | 510.2 | 8.45 | 14.04 | smooth |
| 0.272 | 64.9 | | 8.60 | 614.2 | 9.46 | 14.04 | smooth |
| 0.161 | 45.1 | | 8.79 | 426.1 | 9.45 | 14.04 | smooth |
| 0.114 | 53.0 | | 4.88 | 301.1 | 5.68 | 14.04 | smooth |
| 0.170 | 65.5 | | 5.30 | 354.2 | 5.40 | 14.04 | smooth |
| 0.204 | 65.5 | | 6.36 | 443.8 | 6.77 | 14.04 | smooth |
| 0.225 | 65.8 | | 6.97 | 498.0 | 7.56 | 14.04 | smooth |
| 0.241 | 71.6 | | 6.58 | 553.2 | 7.72 | 14.04 | smooth |
| 0.255 | 77.7 | | 6.26 | 573.6 | 7.38 | 14.04 | smooth |
| 0.116 | 70.4 | | 3.24 | 301.1 | 4.28 | 14.04 | steps |
| 0.144 | 80.8 | | 3.28 | 342.0 | 4.23 | 14.04 | steps |
| 0.173 | 94.5 | | 3.11 | 365.2 | 3.86 | 14.04 | steps |
| 0.113 | 57.7 | 0.273 | 4.27 | 276.1 | 4.78 | 14.04 | steps |
| 0.142 | 63.7 | 0.288 | 4.61 | 332.5 | 5.22 | 14.04 | steps |
| 0.170 | 68.5 | 0.313 | 4.95 | 385.9 | 5.63 | 14.04 | steps |
| 0.198 | 71.8 | 0.341 | 5.37 | 438.3 | 6.10 | 14.04 | steps |
| 0.226 | 75.0 | 0.365 | 5.77 | 481.0 | 6.41 | 14.04 | steps |
| 0.114 | 59.3 | 0.264 | 4.13 | 274.9 | 4.63 | 14.04 | steps |
| 0.143 | 65.0 | 0.283 | 4.52 | 293.5 | 4.52 | 14.04 | steps |
| 0.201 | 75.0 | 0.334 | 5.13 | 399.6 | 5.33 | 14.04 | steps |
| 0.230 | 78.8 | 0.357 | 5.45 | 483.7 | 6.14 | 14.04 | steps |
| 0.113 | 31.9 | 0.133 | 10.43 | 371.9 | 11.67 | 26.57 | smooth |
| 0.142 | 38.5 | 0.098 | 9.83 | 419.4 | 10.91 | 26.57 | smooth |
| 0.170 | 41.3 | 0.114 | 10.62 | 431.3 | 10.45 | 26.57 | smooth |
| 0.198 | 45.7 | 0.122 | 10.63 | 464.8 | 10.17 | 26.57 | smooth |
| 0.227 | 50.5 | 0.144 | 10.46 | 501.7 | 9.94 | 26.57 | smooth |

| *Q* ($m^3$/s) | *$D_1$* (mm) | *$C_m$* | *$F_1$* | *$D_2$* (mm) | *$D_2/D_1$* | *Slope* (deg) | *Chute Type* |
|---|---|---|---|---|---|---|---|
| 0.255 | 56.1 | 0.135 | 10.05 | 537.7 | 9.59 | 26.57 | smooth |
| 0.114 | 28.2 | 0.138 | 12.56 | 352.0 | 12.48 | 26.57 | smooth |
| 0.140 | 34.4 | 0.104 | 11.52 | 386.2 | 11.22 | 26.57 | smooth |
| 0.113 | 28.7 | 0.101 | 12.20 | 355.7 | 12.40 | 26.57 | smooth |
| 0.142 | 36.0 | 0.096 | 10.88 | 402.0 | 11.18 | 26.57 | smooth |
| 0.170 | 40.2 | 0.101 | 11.05 | 439.5 | 10.94 | 26.57 | smooth |
| 0.198 | 44.0 | 0.109 | 11.26 | 490.1 | 11.15 | 26.57 | smooth |
| 0.227 | 46.5 | 0.130 | 11.84 | 538.9 | 11.60 | 26.57 | smooth |
| 0.255 | 47.9 | 0.148 | 12.73 | 584.9 | 12.21 | 26.57 | smooth |
| 0.113 | 49.8 | 0.370 | 5.34 | 289.6 | 5.82 | 26.57 | steps |
| 0.142 | 55.5 | 0.373 | 5.67 | 332.5 | 5.99 | 26.57 | steps |
| 0.170 | 60.1 | 0.382 | 6.05 | 381.3 | 6.34 | 26.57 | steps |
| 0.198 | 64.2 | 0.387 | 6.38 | 430.4 | 6.71 | 26.57 | steps |
| 0.227 | 70.3 | 0.402 | 6.36 | 493.5 | 7.02 | 26.57 | steps |
| 0.255 | 67.8 | 0.434 | 7.56 | 524.9 | 7.74 | 26.57 | steps |
| 0.113 | 48.3 | 0.378 | 5.60 | 274.0 | 5.68 | 26.57 | steps |
| 0.142 | 55.9 | 0.369 | 5.61 | 330.7 | 5.92 | 26.57 | steps |
| 0.170 | 63.2 | 0.364 | 5.61 | 383.4 | 6.06 | 26.57 | steps |
| 0.199 | 69.7 | 0.371 | 5.66 | 447.1 | 6.41 | 26.57 | steps |
| 0.227 | 74.3 | 0.385 | 5.86 | 499.9 | 6.73 | 26.57 | steps |
| 0.255 | 71.9 | 0.399 | 6.93 | 539.8 | 7.50 | 26.57 | steps |
| 0.113 | 27.3 | 0.162 | 13.18 | 403.6 | 14.81 | 51.34 | smooth |
| 0.142 | 31.7 | 0.141 | 13.14 | 443.2 | 13.98 | 51.34 | smooth |
| 0.170 | 40.5 | 0.124 | 10.90 | 502.0 | 12.38 | 51.34 | smooth |
| 0.198 | 40.7 | 0.139 | 12.66 | 523.3 | 12.87 | 51.34 | smooth |
| 0.227 | 41.9 | 0.150 | 13.82 | 568.5 | 13.56 | 51.34 | smooth |
| 0.255 | 44.4 | 0.159 | 14.28 | 620.9 | 14.00 | 51.34 | smooth |
| 0.113 | 28.8 | 0.120 | 12.12 | 393.5 | 13.65 | 51.34 | smooth |
| 0.141 | 35.1 | 0.136 | 11.26 | 439.2 | 12.52 | 51.34 | smooth |
| 0.170 | 35.4 | 0.124 | 13.34 | 519.7 | 14.67 | 51.34 | smooth |
| 0.199 | 38.3 | 0.130 | 13.87 | 538.9 | 14.07 | 51.34 | smooth |
| 0.227 | 40.9 | 0.155 | 14.40 | 571.8 | 13.99 | 51.34 | smooth |
| 0.256 | 43.3 | 0.190 | 14.87 | 623.3 | 14.40 | 51.34 | smooth |
| 0.198 | 31.5 | 0.212 | 18.55 | 497.4 | 15.78 | 51.34 | smooth |
| 0.255 | 55.5 | 0.177 | 10.22 | 597.4 | 10.77 | 51.34 | smooth |
| 0.256 | 44.7 | 0.165 | 14.19 | 627.3 | 14.03 | 51.34 | smooth |
| 0.171 | 40.0 | 0.131 | 11.21 | 507.8 | 12.69 | 51.34 | smooth |

| *Q* ($m^3/s$) | *D₁* (mm) | $C_m$ | $F_1$ | $D_2$ (mm) | $D_2/D_1$ | *Slope* (deg) | *Chute Type* |
|---|---|---|---|---|---|---|---|
| 0.113 | 42.4 | 0.443 | 6.80 | 318.5 | 7.52 | 51.34 | steps |
| 0.142 | 49.4 | 0.459 | 6.75 | 381.0 | 7.71 | 51.34 | steps |
| 0.170 | 52.0 | 0.491 | 7.53 | 438.9 | 8.44 | 51.34 | steps |
| 0.198 | 56.1 | 0.504 | 7.81 | 475.2 | 8.47 | 51.34 | steps |
| 0.227 | 62.3 | 0.500 | 7.65 | 525.5 | 8.44 | 51.34 | steps |
| 0.255 | 65.2 | 0.510 | 8.03 | 574.2 | 8.81 | 51.34 | steps |
| 0.113 | 41.4 | 0.458 | 7.05 | 354.5 | 8.57 | 51.34 | steps |
| 0.142 | 47.8 | 0.480 | 7.10 | 410.9 | 8.60 | 51.34 | steps |
| 0.170 | 52.4 | 0.481 | 7.41 | 468.8 | 8.94 | 51.34 | steps |
| 0.198 | 55.8 | 0.504 | 7.88 | 522.1 | 9.36 | 51.34 | steps |
| 0.227 | 60.1 | 0.515 | 8.05 | 567.5 | 9.45 | 51.34 | steps |
| 0.255 | 63.4 | 0.516 | 8.36 | 611.4 | 9.65 | 51.34 | steps |

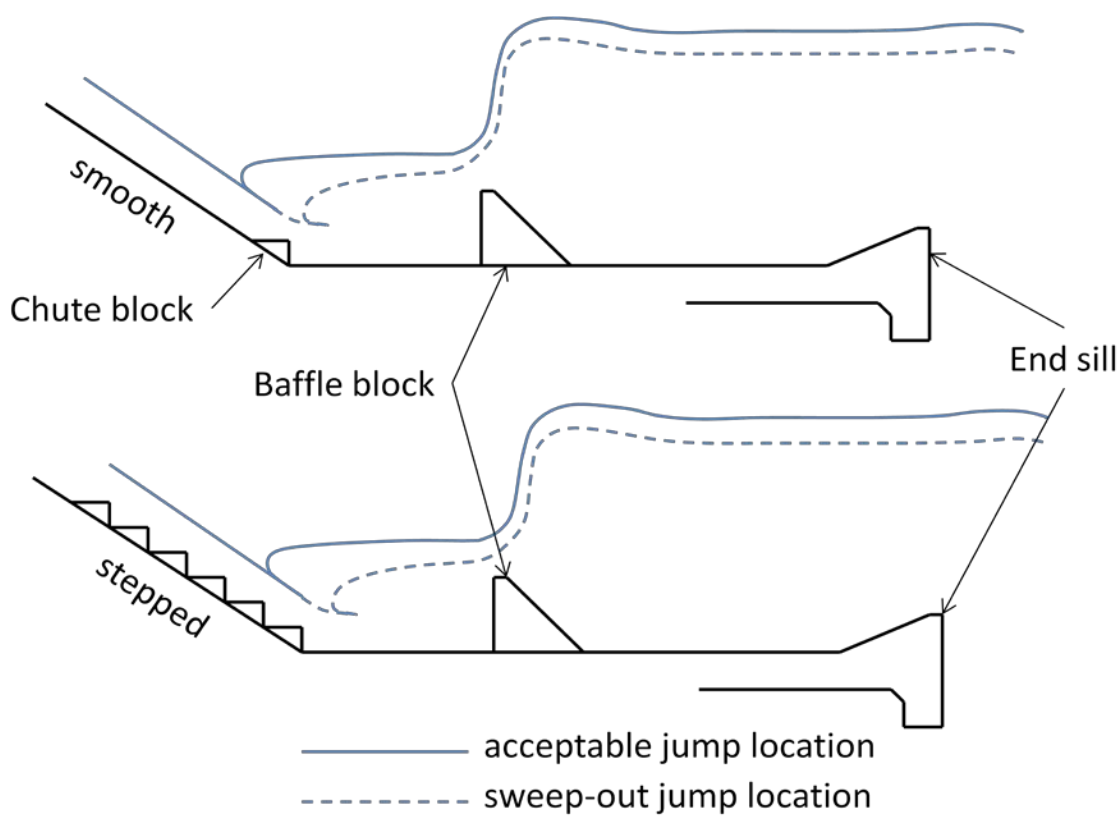


**Figure 6:** Water surface profiles for the smooth and stepped chutes showing relative location of the toe of the jump for acceptable (on the chute slope) versus sweep-out (on the horizontal floor) conditions for tailwater.

The initial analysis of the data consisted of duplicating plots found in Monograph 25, and using the smooth chute type III verification data that is presented. The first parameters to be plotted are the incoming Froude number, $F_1$ versus $D_2/D_1$ (or tailwater over incoming depth). Figure 7 shows all smooth chute data collected and compared to the original type III verification data presented by Peterka (1978). 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 85.5-percent of the full sequent depth of an unconstrained jump (black line). Interestingly, the data from the present study when best fit with a linear regression, plot at about 78-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 (figure 6).

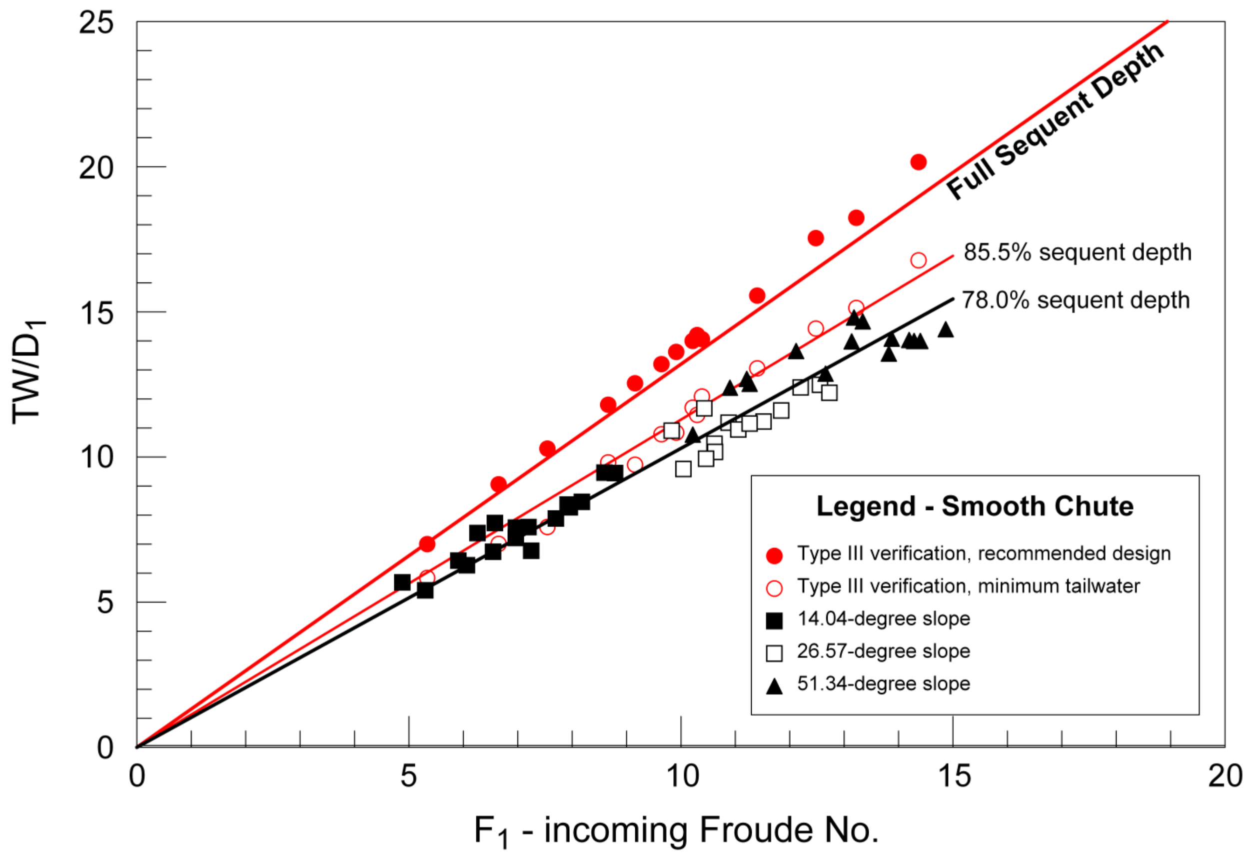


**Figure 7:** Smooth chute data shown with type III verification data from Peterka (1978). Peterka's minimum tailwater (TW) data was 85.5-percent of sequent depth; new data (acceptable) for all slopes is 78.0-percent of sequent depth.

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 data on figure 8 show the $D_1$ measurement in two ways. Initially at the flatter slope, when air entrainment was not considerable, the ultrasonic distance meter was used to detect the upper water surface. Then as air entrainment increased with increasing slope, this meter was abandoned for a method where mean air concentration of the flow entering the stilling basin was measured in order to calculate a clear-water depth. 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 3-percent will affect both the $D_2/D_1$ ratio (dropping it by the same percentage) and $F_1$ (dropping it by 4.6-percent). These changes move the best-fit regression line to the left, providing the impression of a higher required tailwater for a given $F_1$.

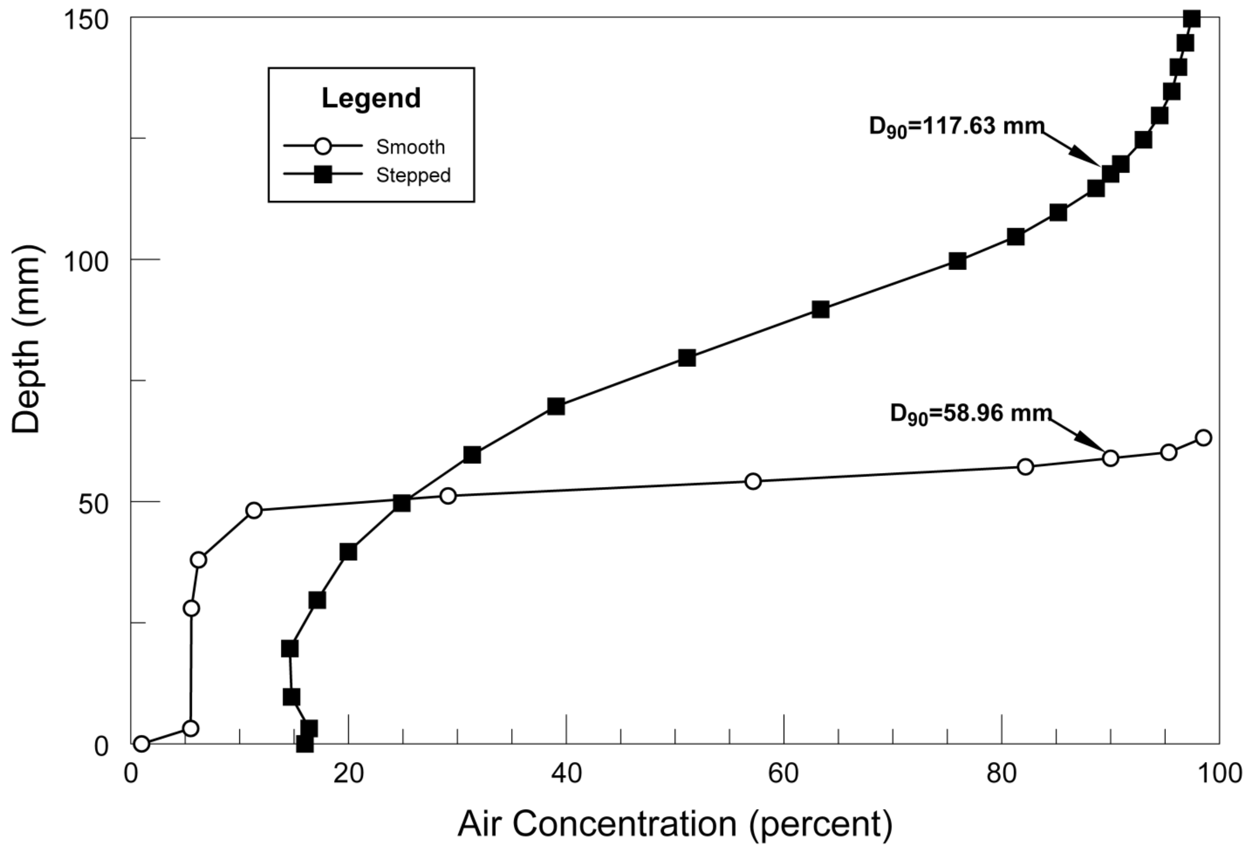


**Figure 8:** Air concentration profiles for smooth and stepped chutes on the 26.57-degree slope at a discharge of 0.227 $m^3/s$ (8 $ft^3/s$). Note the substantial increase in the depth at 90-percent air concentration for the stepped chute. (1 ft = 304.8 mm)

Figure 9 shows a sample from the 26.57-degree slope data of the ultrasonic probe depth compared to the clear water depth computed from the mean air concentrations at the same locations. The lower set of data is from the smooth chute (air concentrations from 9.5- to 14.7-percent) and the higher set is from the stepped chute (air concentrations from 36.4- to 43.4-percent). It appears that up to an air concentration of about 10-percent there is good agreement with the two measurement methods. All slopes with steps installed were above this threshold and required air concentration profiles to determine the incoming depth (clear water depth).

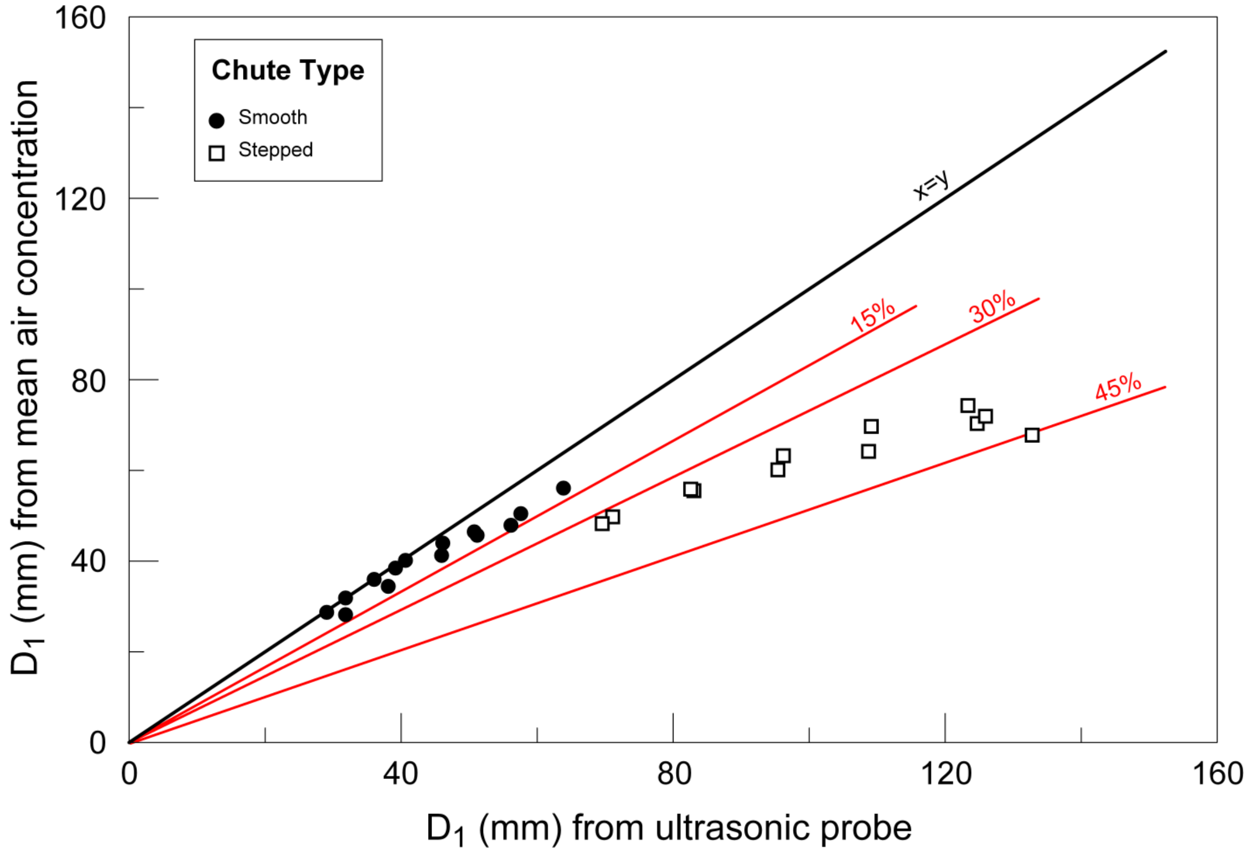


**Figure 9:** *$D_1$* measurement from MassaSonic™ probe compared to the *$D_{cw}$* computed from air concentration measurements for the 26.57-degree slope, smooth and stepped chutes. (1 ft = 304.8 mm). Red lines represent approximate mean air concentration levels.

Data from the stepped chute for the three different slopes are shown in figure 10. As can be seen from table 1, for similar specific discharges, the incoming Froude numbers are considerably lower than for the smooth chute. This occurs because incoming velocities are reduced at the point of measurement due to energy dissipation on the steps and substantially increased depths result due to bulking by increased air entrainment. The three stepped chute data sets compare well to the type III verification sweep-out data from the smooth chutes. Photos at each of the three slopes are shown in figure 11.

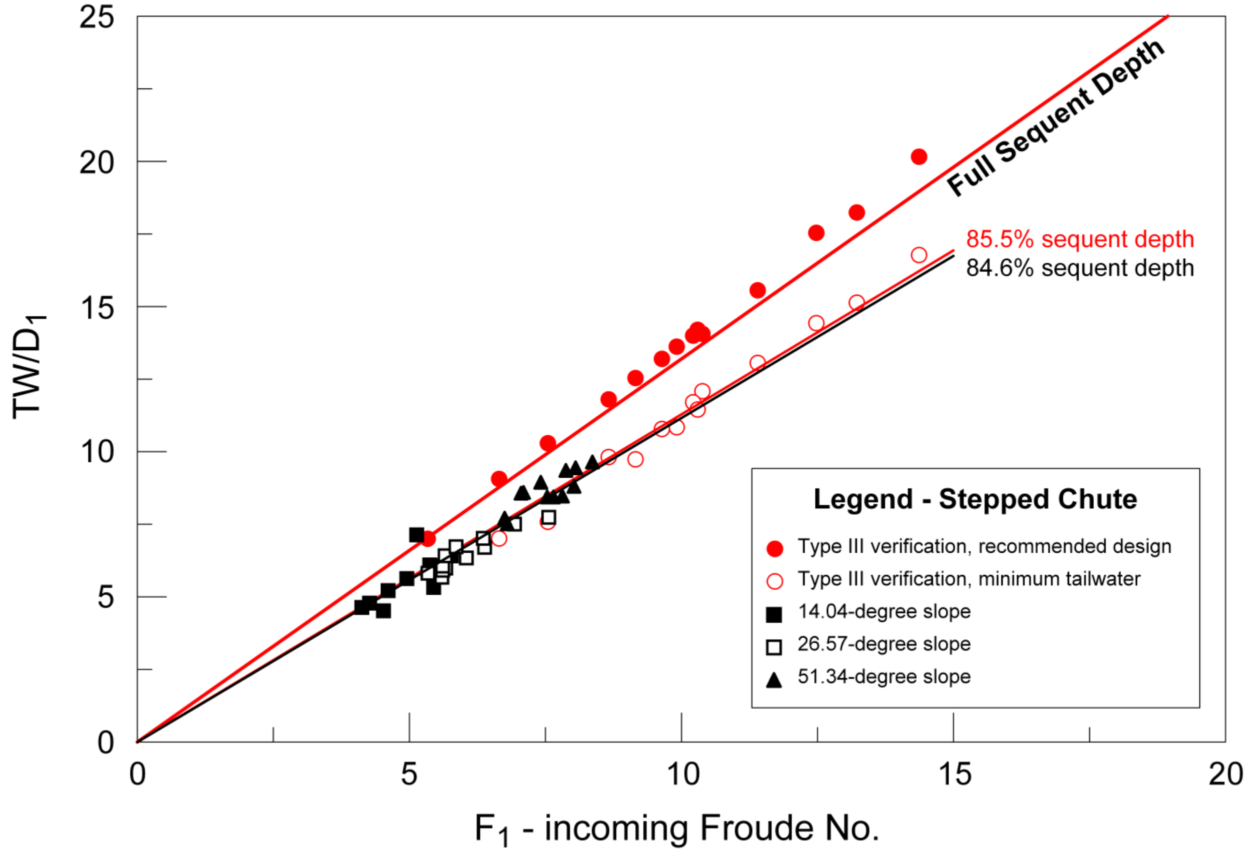


**Figure 10:** Incoming Froude number based on clear water depth versus tailwater over $D_1$. Data from present study reflects acceptable basin performance, i.e. . toe of the hydraulic jump is on the chute slope.


a) 14.04-degree (4 to 1) stepped chute


b) 26.57-degree (2 to 1) stepped chute


c) 51.34-degree (0.8 to 1) stepped chute

**Figure 11:** View of each of three slopes, showing jet box and the beginning of the stepped chute.

For the stepped chute data, the tailwater was lowered to a sweep out condition with both the standard baffle blocks and the supercavitating baffle blocks. The lowest discharges did not require tailwater downstream from the basin to maintain an acceptable jump within the basin. A stable hydraulic jump was formed and maintained with only the basin appurtenances. Figure 12 shows the tailwater data at sweep out for the stepped chute cases.  Below a Froude number of 6 the $TW/D_1$ ratio approaches zero. For $F_1$>6 the data follows a trend resulting in about a 13-percent reduction in required tailwater from the acceptable data (figure 10) or 30-percent less than $D_2$ representing the full sequent depth.

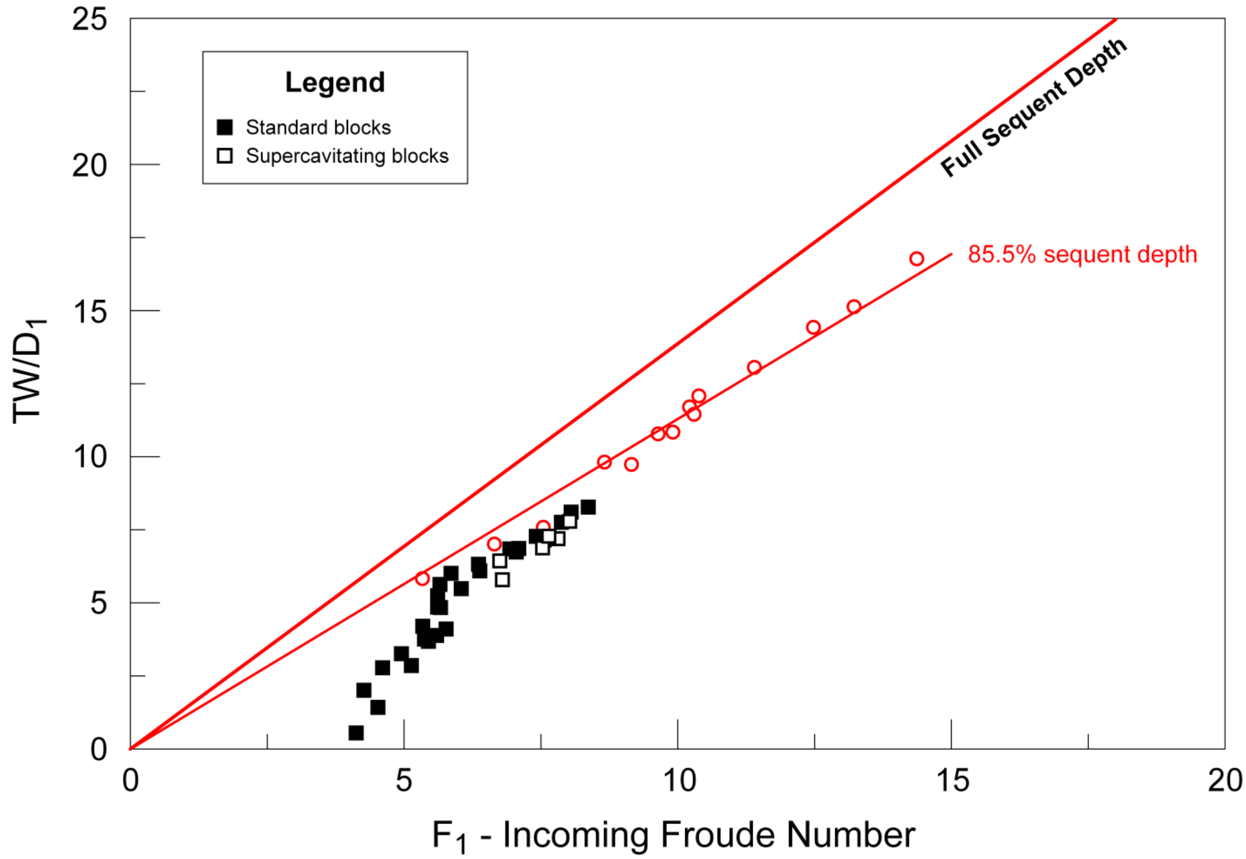


**Figure 12:** Sweep out data for the stepped chutes with both style baffle blocks.  Note the steep decrease in tailwater requirement below an incoming Froude number of about 6.

## Discussion

From the prior work on the Folsom Dam auxiliary spillway stilling basin (Svoboda et.al. 2010), it was noted that improved stability with lowering of tailwater was evident with the modified, supercavitating baffle block design and floor ramps between the blocks.  Originally tests were conducted to show if this improvement was due to the ramps or related to performance of the basin with a stepped chute versus a smooth chute.  During this current test program, the standard baffle block design was tested with and without ramps and actually noted an opposite trend, i.e. more tailwater was needed with ramps installed.  However, when the supercavitating baffle block design was installed a definite decrease in required tailwater was noted.  Little difference was noted between the performances of the supercavitating block with and without floor ramps; however, supercavitating baffle blocks required 12-percent less tailwater than standard blocks when floor ramps were installed and 6-percent less tailwater when ramps were not installed (figure 13). Figure 14 shows a wireframe drawing of the standard baffle block and the supercavitating baffle block design without floor ramps between blocks.  Figure 15 shows a photograph of the floor ramps between the supercavitating blocks.

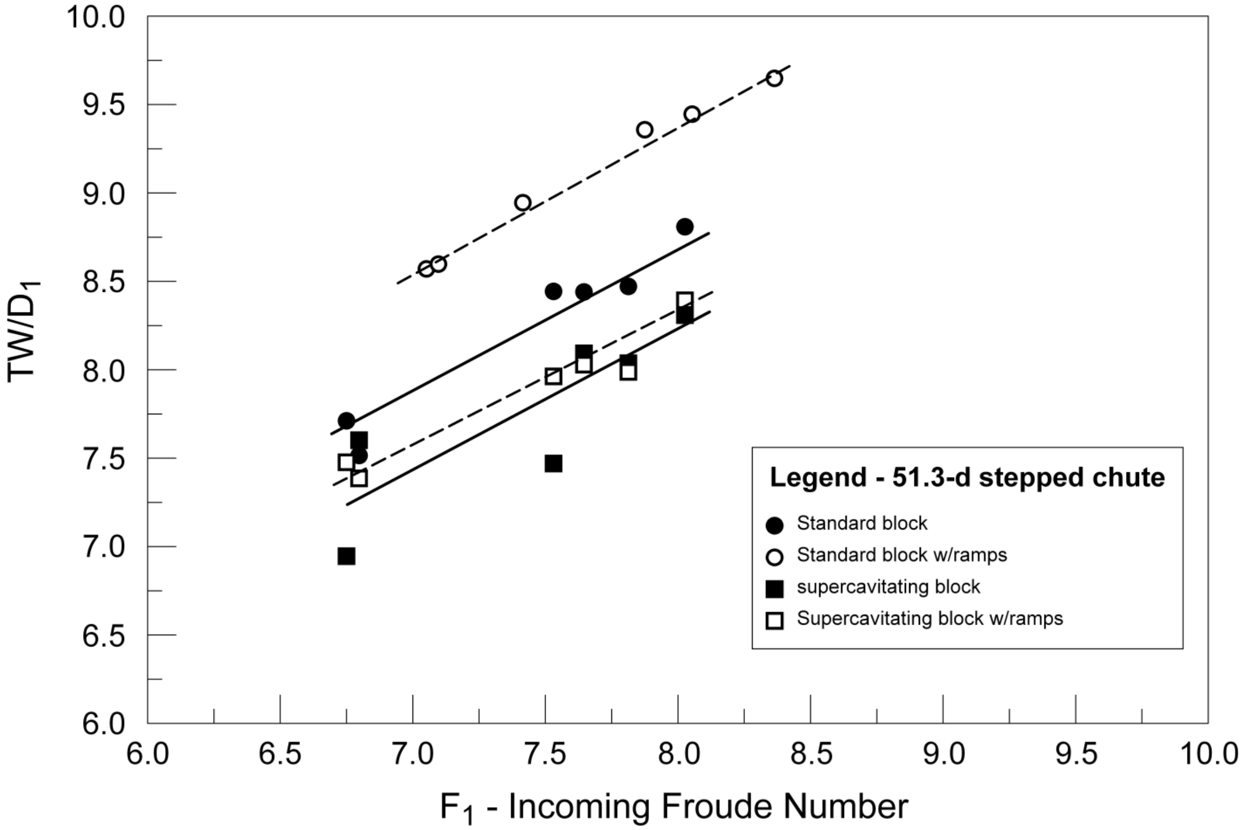


**Figure 13:** Influence of baffle block design and ramp performance on tailwater requirements for the 53.1-degree stepped chute.

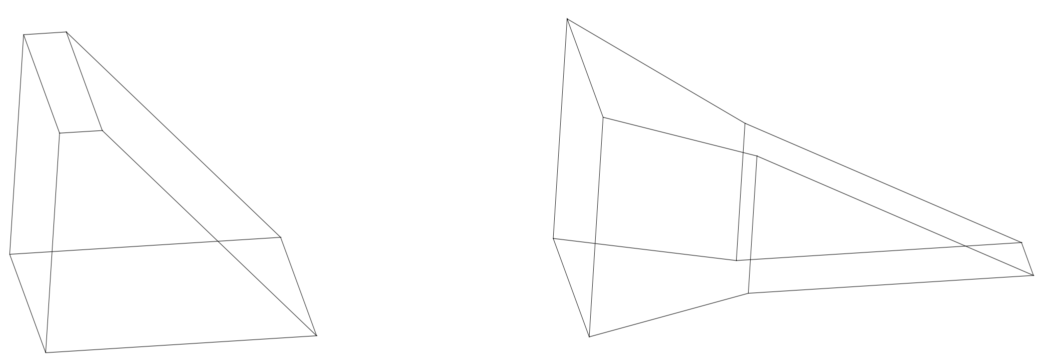

**Figure 14:** Wireframe sketches of the standard block on left and supercavitating block on the right.

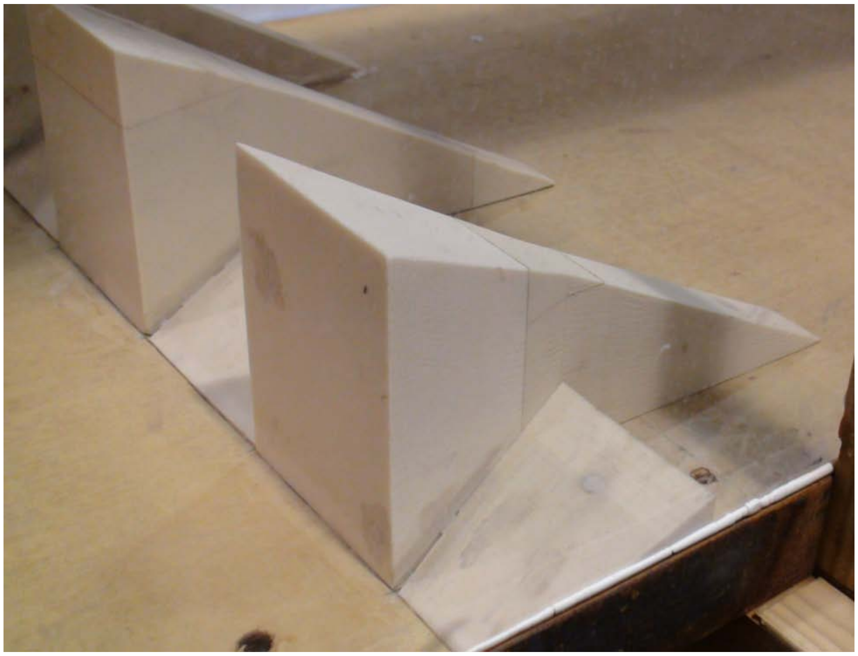

**Figure 15:** View of stilling basin model with supercavitating baffle blocks and floor ramps installed.

The current study 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 16 shows a plot of $F_1$versus the ratio of basin length to tailwater. Data from the smooth and 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 (both smooth and stepped chutes) 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 typical of the stepped chutes.

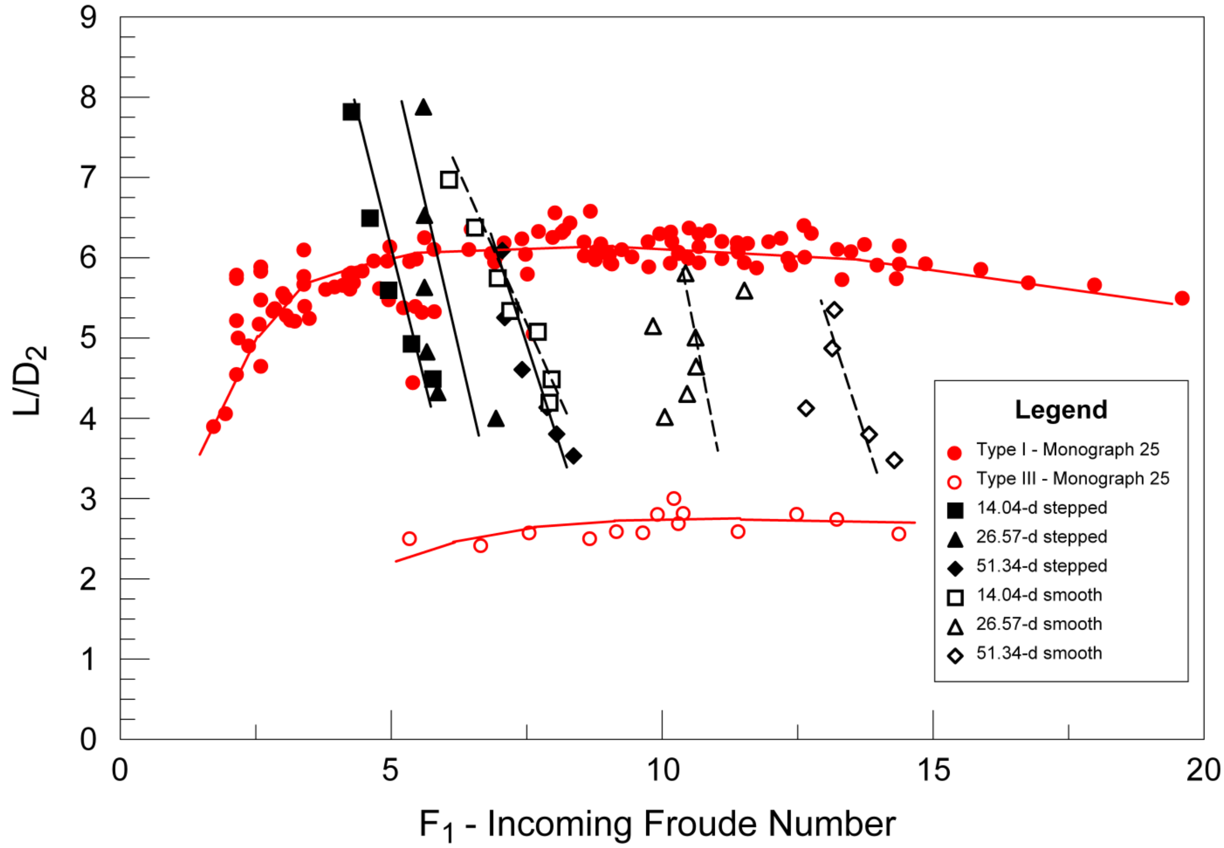


**Figure 16:** Smooth and stepped data plotted versus verification data for type I and type III stilling basins, Peterka (1978).

## Conclusions

The use of type III stilling basins with stepped spillways appears to be quite acceptable based on results of the current study. The use of the clear-water parameters for stepped spillway designs allows consistent application of the current design principles for type III stilling basins detailed in Reclamation's Engineering Monograph No. 25 (1978). Measurements of the incoming depth, $D_1$ and velocity, $V_1$ are probably the most important aspects, realizing that even flows on smooth chutes at high Froude numbers can have significant air entrainment resulting in air-bulked flow entering the stilling basin. Bradley and Peterka's initial studies used averaged visual point gage measurements to determine $D_1$ and then calculated $V_1$. Although the effect of air entrainment is magnified with flows down stepped chutes, the smooth chute flows modeled in these early experiments clearly faced some issues regarding measured flow depths and their impact on the design procedure. Establishing the appropriate methods for basin design with stepped chutes becomes increasing important as air concentrations are significant even at flatter slopes and small Froude numbers.

The design parameters detailed in Peterka (1978) appear to have a substantial factor of safety regarding the necessary tailwater depth for acceptable stilling basin performance. The present studies have found that for both smooth and stepped chutes, acceptable performance can be attained at ratios of $D_2$ (TW) to $D_1$ of 20- to 25-percent less than full sequent depth values. In addition for stepped chutes at incoming Froude numbers $F_1$ less than about 6, significantly less tailwater is required, to the point that under certain conditions the jump will be maintained in the basin strictly by the appurtenant structures within. Finally, basin tailwater performance is also improved by 6- to 12-percent of $D_2/D_1$ by using the supercavitating baffle block design developed for the Folsom Dam auxiliary spillway. It appears that additional energy dissipation takes place due to the forced recirculation (wake) zones on the block's sides and top surfaces (in contrast to the parallel block surfaces of the standard design). Scale effects in the modeling of stilling basin performance, in particular the effects of air entrainment, have largely been ignored in many of the previous studies on this topic. Interestingly, the design parameters detailed within Reclamation's Monograph No. 25 have been shown in the present study to be valid when adjustments are made for the depth-averaged mean air concentrations to the design flow parameters. The prior mention of a substantial factor of safety has likely been responsible for adequate basin performance at the prototype scale when large amounts or entrained air are present.

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