USBR TYPE III STILLING BASIN PERFORMANCE FOR STEEP STEPPED SPILLWAYS

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Abstract: Stepped spillways are known to have a higher energy dissipation potential when compared to a smooth invert chute of identical slope. Therefore, the length of downstream energy dissipators can be reduced. To date, little is known about the effect of the stepped profile on the stilling basin performance. Therefore, new measurements were carried out on a large-scale stepped spillway model in combination with a USBR type III stilling basin, where conventional and modified chute blocks were analysed. Pressure heads and flow depths along the basin were measured systematically for several flow rates and tailwater conditions. The results follow the recommendations by the USBR for type III basins except at the basin entrance, similarly as observed in previous studies. The conventional or modified chute blocks were found to have a minor influence on the pressure head.

Keywords: stilling basin, hydraulic jump, stepped spillway, physical modeling, pressure head.

INTRODUCTION

Due to increasing popularity of stepped spillways, this type of chute has motivated significant research worldwide. Most of these studies, particularly those for stepped spillways over RCC dams, have focused on the skimming flow regime, which commonly occurs for the design discharge. In this regime, which sets in with increasing discharges for a given slope and step height, water flows down as a coherent stream above the pseudo-bottom formed by the step edges. While only a few studies investigated the non-aerated flow region near the crest (e.g., Amador et al. 2006, Gonzalez and Chanson 2007, Bombardelli et al. 2011), numerous investigations focused on the aerated region, particularly on the assessment of parameters as air concentration and flow velocity (e.g., Matos 2000, Chanson 2002, Bung 2011), pressure fields on the step surfaces (e.g., Yasuda and Ohtsu 2003, Sánchez-Juny et al. 2008) and characteristics of the inception point of air entrainment (e.g., Boes and Hager 2003, Pfister and Hager 2011).

Only very few studies dealt with the hydraulics of energy dissipators downstream of stepped spillways. Meireles et al. (2005) and Cardoso et al. (2007) studied a simple hydraulic jump basin and a baffle basin, respectively, concluding that the pressure head along the basin is almost independent of the step height for a given discharge. Equations to determine the pressure head along the basins have been proposed in both studies. Cardoso et al. (2007) and Meireles et al. (2010) studied USBR type I and III stilling basin performance for 2 and 4 cm high stepped chutes, respectively, and evaluated their influence on the pressure profiles. In the latter case, the basin performance using modified chute blocks was also investigated. The development of the normalized pressure head on the basin floor was found to be practically independent of the step height. Also, the stilling basin performance was not influenced by the modified chute blocks. In spite of these initial studies, a more detailed investigation on the appurtenance effects and tailwater depths was considered necessary.The purpose of this study is to extend the previous work carried out at LNEC, namely by analysing the energy dissipator's performance downstream of a steep stepped spillway with a larger step height. As USBR basins have been developed for smooth invert chutes, chute blocks cannot be installed in a similar way, without readjusting the stepped chute profile in the vicinity of the toe. Hence, three different cases were investigated (Fig. 1): i) a test group without chute blocks (TG1); ii) a prismatic block with a height obtained according to the USBR design criteria developed by Peterka 1958 (TG2); and iii) a conventional chute block in combination with a filled step niche (TG3), which reflects the original geometry in case of a smooth invert chute. The design of the appurtenances for TG1 and TG2, as well as experiments for TG1 (with the exception of the lower discharge) were performed in the framework of Meireles (2011), whereas additional tests for TG1 and all the other tests were carried out in the framework of Sun (2011).

EXPERIMENTAL SETUP

A facility assembled at the National Laboratory of Civil Engineering (LNEC), in Portugal, was used to conduct the experimental study. The installation comprises a stepped chute 2.90 m high, 1.00 m wide, and with a slope of 1V:0.75H and 8 cm high steps. The downstream channel is 5.00 m long and 1.00 m wide and includes the stilling basin. The stilling basin has been designed in accordance to the USBR recommendations for type III basins, based on the basin inflow conditions determined from empirical expressions developed by Meireles (2004). The appurtenance geometries are indicated in Fig. 1. Measurements of flow depths and bottom pressure heads along the stilling basin were visually collected for specific discharges q between 0.08 and 0.20 m²/s corresponding to skimming flow regime on the approaching chute. Piezometric taps were installed on the stilling basin floor and connected to a piezometric panel to obtain pressure heads along the complete stilling basin and the downstream region. The location of the piezometric taps are given in Fig. 2. Pressure head values for taps A1/A2, E1/E2 and F1/F2 are averaged for subsequently presented data analyses. Flow depths were measured at the cross-sections of piezometer 1-18 by applying rulers on the transparent channel walls. It should be noted that all presented results refer approximately to averaged values due to turbulent measuring fluctuations. Discharges were checked by use of a Bazin weir in the downstream channel and a downstream sluice gate was used for regulation of the tailwater depth.

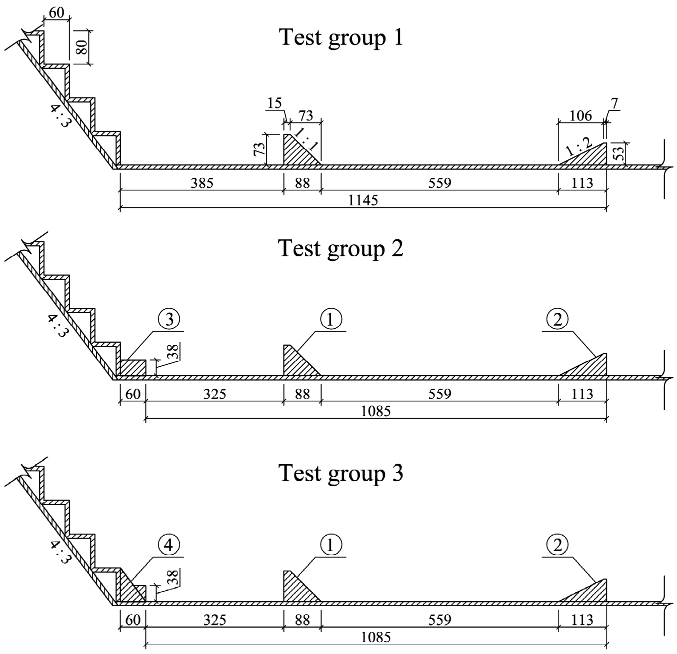
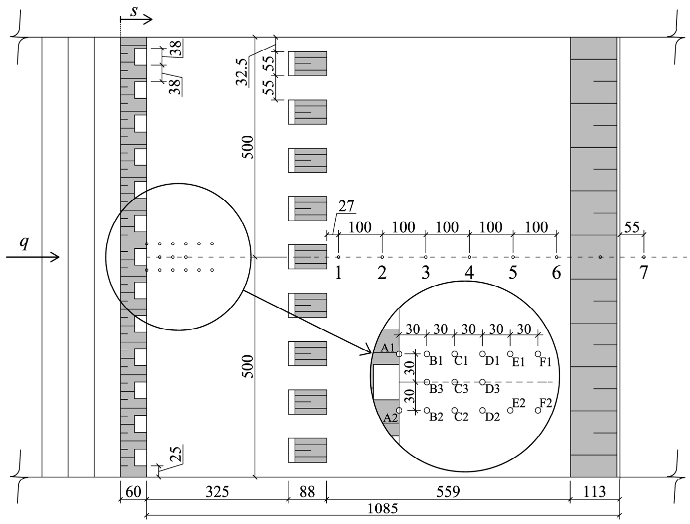


Figure 1 - Experimental setups of the stilling basin with 9 baffle piers (1) and an end sill (2), Test group 1: USBR type III without chute blocks, Test group 2: USBR type III with 13 prismatic chute blocks (3), Test group 3: USBR type III with 13 original chute blocks in combination with filled step niche (4), all dimensions in [mm]



Tap No.	*s* [m]	Tap No.	*s* [m]
8	1.45	16	2.25
9	1.55	17	2.50
10	1.65	18	2.60
11	1.75	19	2.70
12	1.85	20	2.80
13	1.95	21	2.90
14	2.05	22	3.00
15	2.15	23	3.10

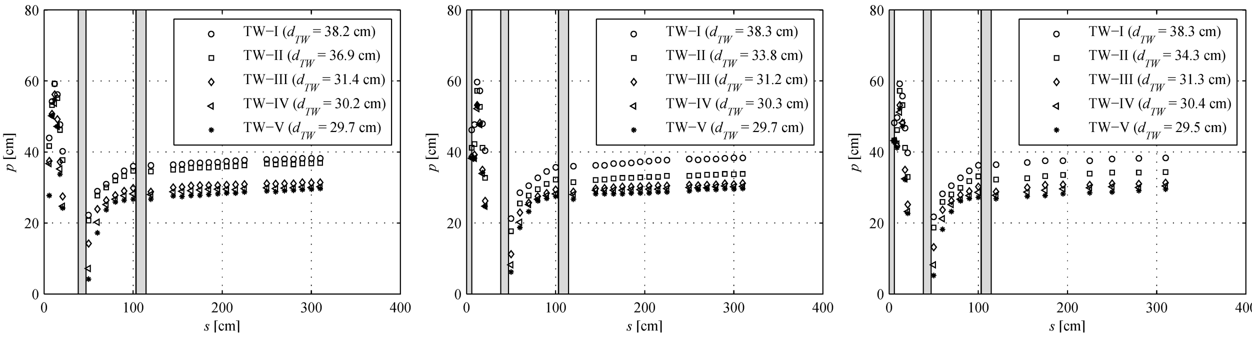
Figure 2 - Location of the piezometric taps in the stilling basin (here: illustrated for test group 3 setup), all dimensions in [mm], distance *s* of downstream piezometric taps from the spillway toe

RESULTS

Variation of the tailwater depth for the design case

For the design discharge q = 0.18 m²/s, the piezometric heads were investigated with different tailwater depths, d_{TW}, for each test group TG1, TG2 and TG3. The following indexes are used to indicate different tailwater depths:

- TW-I: fully conjugate tail water depth;
- TW-II: the toe of the hydraulic jump is above the intersection line of the step edges with the stilling basin bottom (for TG1 the toe of the hydraulic jump is kept above the last step);
- TW-III: free hydraulic jump;
- TW-IV: the hydraulic jump is periodically swept out of the basin;
- TW-V: the hydraulic jump is almost permanently swept out of the basin.



(a) Test group 1 (TG1) (b) Test group 2 (TG2) (c) Test group 3 (TG3)

Figure 4 - Centerline pressure heads p along the stilling basin length s (colored regions mark the location of the appurtenances) for different tailwater conditions and for the design discharge

Observed centerline pressure head distributions are illustrated in Fig. 4, including the averaged values for taps A1/A2, E1/E2 and F1/F2. As expected, the qualitative results are not affected by the tailwater depth as well as by the presence and geometry of the chute blocks. In a quantitative view, the maximum pressure heads, $p_{\max}$, at the impinging region do not depend on the tailwater condition and test group. Instead, $p_{\max}$ is found to be approximately $3.8d_c$ and, thus, to be only influenced by the discharge. On the other hand, the minimum pressure heads immediately downstream of the baffle piers are very sensitive to tailwater variation, decreasing significantly as compared to the hydrostatic pressures near the downstream end of the jump. In fact, the bottom jet flow is expected to impact the baffle piers more directly with the reduction of tailwater depth, once the roller-generating surface back flow above the bottom jet is reduced. Downstream of the baffle piers, the resulting high flow velocity causes much lower pressures than those corresponding to the hydrostatic pressure head. The end sill forces the bottom jet flow to deflect towards the water surface, therefore a kind of swell was obtained downstream of the end sill in “TW-IV” and “TW-V”. Near the downstream end of the jump, the pressure heads are practically equal to those corresponding to the hydrostatic pressure distribution.

Variation of discharge for given tailwater depths

The following discharges were studied herein: q = 0.08, 0.14 and 0.20 m²/s. For each discharge the stilling basin was tested for submerged hydraulic jumps (by increasing the tailwater depth to fully conjugate depth as recommended by Peterka (1958), identical to TW-I in the previous subsection: suffix “I”) and for free hydraulic jumps (by lifting the downstream gate, identical to TW-III in previous subsection: suffix “III”). Measured centerline pressure heads for all test groups and tailwater conditions are illustrated in Fig. 5. As observed by Meireles et al. (2010), the pressure head along the stilling basin increases with increasing discharge. Furthermore, p is significantly larger at the impact region than the corresponding value for a hydrostatic pressure distribution as clear water depths at the spillway toe are 0.016 , 0.030 and 0.040 m for investigated discharges according to design formulas developed by Matos (2000). In accordance to Meireles et al. (2010), the chute block presence or geometry, respectively, have only negligible influence on the overall pressure distribution (particularly from s = 0.12 m). It is believed that the step-induced increase of turbulence on the spillway makes the chute blocks dispensable, whose function is to create a greater number of energy dissipating eddies by lifting a portion of the corrugated jet from the floor (Peterka 1958).

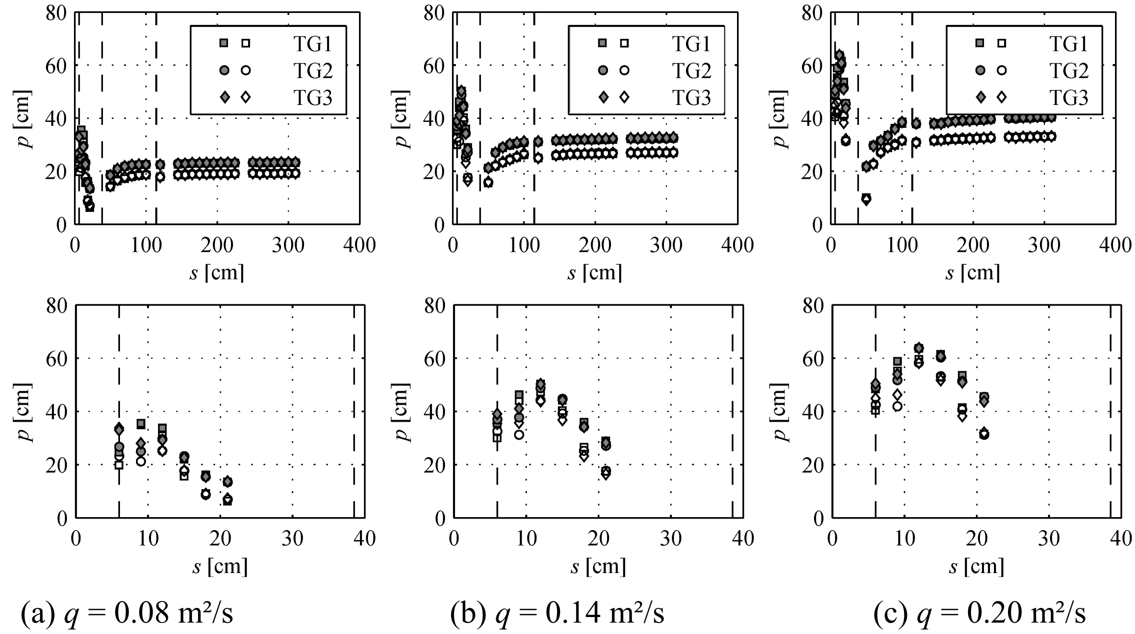


Figure 5 - Centerline pressure heads p along the stilling basin length s (the dashed lines mark the location of appurtenance, i.e. end of chute blocks, beginning of baffle piers, beginning of end sill), top: complete stilling basin, bottom: detail of impinging region downstream of the structure, dark symbols: submerged hydraulic jump TW-I, open symbols: free hydraulic jump TW-III

However, the presence of chute blocks affects the local pressure head directly at the impinging region downstream of the structure. In detail, pressure heads between the chute blocks (i.e., at taps A1 and A2 with s = 0.06 m) are increased up to 17 % for TG2, and approx. 4 to 70 % for TG3. Further downstream of the chute blocks (i.e. at taps B1-B3 with s = 0.09 m) the pressure head differences decrease to 6 to 18 % for TG2, and 3 to 12 % for TG3. Deviations become smaller with increasing discharge, and also smaller for submerged hydraulic jumps than for free hydraulic jumps with identical discharge. Table 1 summarizes the averaged pressure head differences of all piezometric taps A-F within the impinging region for TG2 and TG3 in relation to TG1. As expected, the pressure heads obtained for discharges near the design value are practically not affected by using chute blocks according to TG2 or TG3. The maximum pressure heads, generally found within the impinging region at tap C, are presented in Fig. 6. The finding from the previous section that $p_{\max}$ corresponds to approximately $3.8d_c$ is validated herein for a wider range of discharges. It should be noted that higher pressures may occur as Fig. 6 includes approximate averaged values only.

Tab. 1: Averaged pressure head difference of taps for TG2 and TG3 compared to TG1 (negative values for pressure decrease, positive values for pressure increase)

Test group	q = 0.08 m²/s	q = 0.14 m²/s	q = 0.20 m²/s
TG2-I	-2.0 %	-3.5 %	-1.5 %
TG3-I	3.9 %	-0.3 %	-1.4 %
TG2-III	2.4 %	-2.9 %	-1.8 %
TG3-III	14.0 %	-2.7 %	-0.6 %

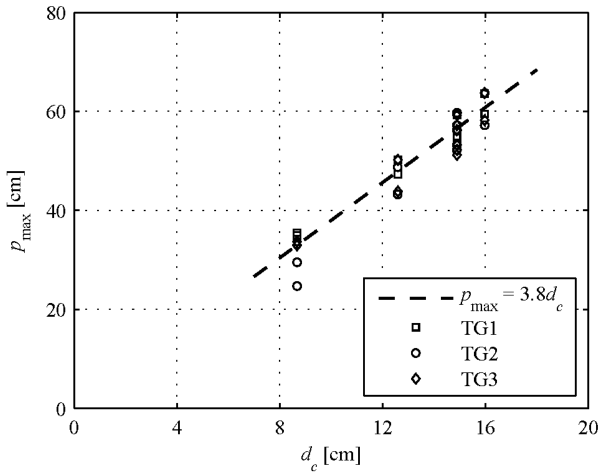


Figure 6 - Maximum pressure heads within the impinging region as a function of the critical water depth d_c for all investigated test runs

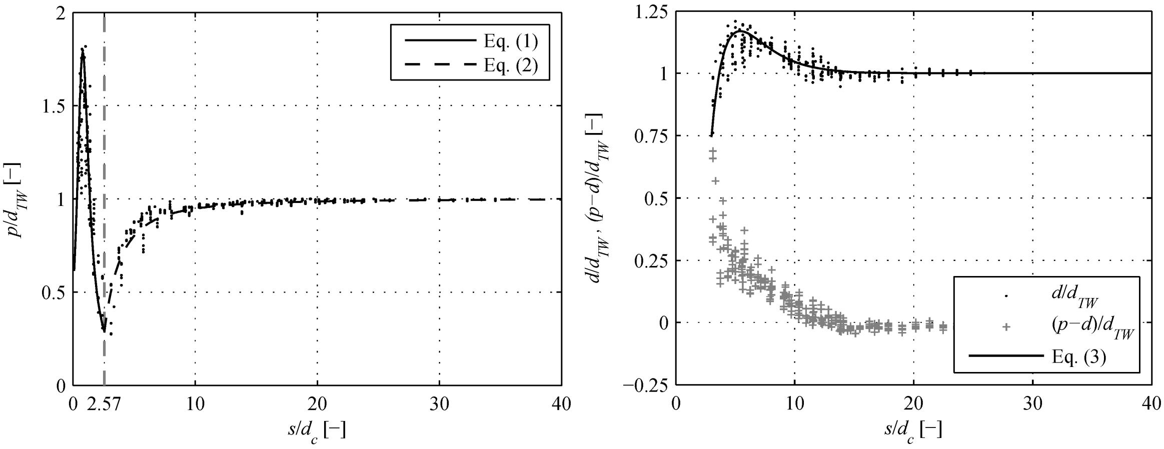
As the minimum pressure heads, $p_{\min}$, occur outside of the impinging region where the distance between adjacent piezometric taps increases, exact values of $p_{\min}$ may be missed in the experiments, as already pointed out by Meireles et al. (2010). In fact, no definite relationship for the minimum pressure heads and other parameters can be detected on the basis of gathered data. However, as previously illustrated in Fig. 5, pressure head distributions show a clear qualitative characteristic. In order to describe p as a function of the distance s, Eq. (1) with $R^2 = 0.91$ and (2) with $R^2 = 0.90$ were obtained for TG1-III (taken as a standard design as chute block effects were negligible):

$$\frac{p}{d_{TW}} = \frac{0.25\left(s/d_c\right)+0.44}{\left(s/d_c\right)^2-1.46\left(s/d_c\right)+0.89} \quad \text{for } s/d_c \le 2.57 \tag{1}$$

$$\frac{p}{d_{TW}} = -4.38\left(s/d_c\right)^{-1.92}+1 \quad \text{for } s/d_c > 2.57 \tag{2}$$

Although both approaches are based on data obtained for the test group TG1 (without any chute blocks) and the free hydraulic jump only, the applicability to all configurations given in Fig. 5 is supported by the good agreement to the complete data set as illustrated in Fig. 7(a). Tailwater depths d_{TW} for application of Eqs. (1) and (2) were found to be $\approx 2.6d_c$ for TW-I and $\approx 2.1d_c$ for TW-III, respectively. As it can be observed, the maximum pressures are about twice the tailwater depth and, thus, exceed the design pressure head recommended by Peterka (1958).A constant pressure head sets in after $s \approx 15d_c$. Figure 7(b) shows that difference between p and d becomes negligible in the gradually varied flow region near the downstream end of the hydraulic jump. It should be noted that d is a bulked flow depth due to air entrainment, which is of particular relevance in the roller region. Thus, the location corresponding to the onset of hydrostatic pressure distributions cannot be defined with complete accuracy. Equation 3 can be used for determination of mean flow depth d. As measurements were limited to the region $0.5\ \mathrm{m} \leq s \leq 2.60\ \mathrm{m}$, no information of the impinging region is available. Although Eq. (3) is based on data of TG1-III again ($R^2 = 0.89$), it may be applicable for estimating flow depths of all test configurations:

$$\frac{d}{d_{TW}} = -\frac{-16.74}{\exp\left(0.66 s/d_c\right)} + \frac{8.71}{\exp\left(0.49 s/d_c\right)} + 1 \quad \text{for } s/d_c > 3 \tag{3}$$



(a) Eqs. (1) and (2) vs. experimental data (b) Eq. (3) vs. experimental data

Figure 7 - Dimensionless pressure distribution p/d_{TW} as a function of the dimensionless distance s/d_c in comparison to Eq. (1) - (3) and experimental data

CONCLUSIONS

In this paper, a study on the performance of USBR type III stilling basins downstream of stepped chutes was conducted. In particular, bottom piezometric heads were analyzed for three configurations with different chute block designs and tailwater conditions. The pressure heads in the impinging region are only slightly affected by the presence or type of chute blocks. In fact, the maximum pressure head is primarily influenced by the discharge. Further downstream, a considerable influence of the tailwater depth was found. Generally, for the given spillway slope, typical for RCC dams, chute blocks seem to be dispensable in USBR type III basin in combination with stepped spillways. An empirical approach accounting for both, discharge and tailwater depth, was developed to determine pressure heads along the stilling basin for any test group. Further tests are needed to characterize the pressure field, namely in the impact region and near the baffle piers.

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