Energy dissipation on stepped spillways with a piano key weir: experimental study

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Abstract

The present work is focused on the study of the hydraulic jump in stilling basins downstream of stepped spillways combined with piano key weirs.

Based on a set of piezometric head and flow depth data acquired on the floor of the Bureau of Reclamation (USBR) type I and III basins, in a facility previously built at the Laboratório Nacional de Engenharia Civil (LNEC) and slightly adapted for the present research, some hydraulic jump properties along the basin downstream of the chute toe are analysed.

From the results obtained on the USBR type I basin, the residual head at the chute toe, as well as the total head loss on the stepped chute, are computed. The results are compared to those obtained in previous experimental studies, namely in stepped spillways combined with piano key or WES type weirs. For the range of test conditions on the LNEC facility, the energy dissipation on the stepped chute combined with the piano key weir is slightly lower than that obtained for an identical stepped chute combined with a WES weir.

Finally, normalized formulae are presented for estimating the residual head at the chute toe or the head loss on stepped spillways combined with piano key weirs.

Keywords: stepped spillway; skimming flow; piano key weir (PKW); stilling basin; hydraulic jump; energy dissipation.

1. Introduction

One crucial aspect in the construction and exploration of a dam is the safety as an accident will always have serious consequences, of greater or lesser degree, depending on the amount of water stored. The orographic characteristics of the region, the people and goods affected by the dam´s failure, in the most drastic situation, may lead to the loss of lives and to a huge material damage.

The availability of larger hydrologic data series, along with the climate change and extreme weather events can lead to higher peak flow values, causing the overtopping of dams due to undersized spillways. Thus, an important aspect to enhance the safety of these structures is to increase their flow release capacity, constituting one of the most common solutions the adoption of the labyrinth type weir. Indeed, this type of weir can increase the discharge, keeping the length associated with the existing conventional weir.

Recently, the company Hydrocoop-France, in collaboration with the University of Biskra, Algeria, have developed a new weir, more effective than the others, almost identical to the labyrinth weir - the Piano Key Weir (PKW). Such weir as the main advantage of increasing of the flow capacity relative to a traditional weir of the same width. The PKW may be easily installed in a limited space, such as the crest of a gravity dam, making it an efficient and economical solution for increasing the discharge capacity, or the reservoir's storage capacity, and consequently to improve the dam safety.

In 2001, François Lempérière applied for the first time a PKW type weir on an existing dam, aiming to obtain a more efficient and an easier weir construction for increasing the dam's flow release capacity. In 2006, a PKW type weir was built for the rehabilitation of the Goulours's dam by EDF (Electricité de France). Since then, various rehabilitation projects for existing dams applying PKW were completed, namely as those by EDF, such as Saint-Marc, Gloriettes, Etroit and Malarce dams.

2. Main parameters of Piano Key Weirs and stilling basins

The Piano Key Weir (PKW) is a recent evolution of the traditional labyrinth weir, having a rectangular shape in plan and slopes on both sides, constituting the inlet and outlet keys. The inlet key is the alveoli that is opened to downstream and is sided by two lateral walls and the downstream crest. The outlet key is the alveoli that is opened to the downstream face and is also sided by two lateral walls but by the upstream crest. The extension of the crest in the stretch upstream or downstream is usually called projection (Figure 1).

The parameters of the PKW are the total width of the weir (W), the total developed crest length (L) and the number of units of the structure (N_u). The unit represents the smallest extension of a complete structure, made by a complete inlet key with two side walls and half of an outlet key on both sides. All of the parameters related to the PKW unit are defined with the index u, whereas the indexes i, o and s are associated to the inlet key, outlet key and to the side wall. Consequently, the main parameters that describe the geometry of the PKW unit are the unit width, W_u, the width of both the inlet and outlet keys, that is W_i and W_o, the height of each key, P_i and P_o, and the slope related to each one, S_i and S_o.

There are four types of PKW known as type A, type B, type C and type D. The PKW type A designated for the present work includes upstream and downstream projections (Figure 1).

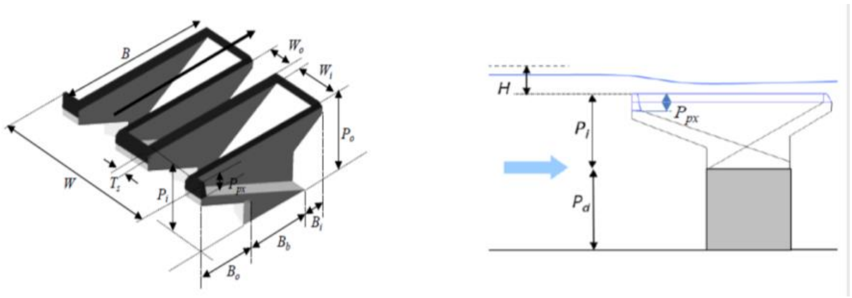


Figure 1 – Fundamental parameters of PKW (adapted from Pralong et al., 2011).

The stilling basins that were addressed in this study included structures that use or not fixed internal blocks to assist in the formation and stable performance of the hydraulic jump downstream of the spillway. Much of the basic theory used in the work of Peterka (1958) was based on a hydraulic jump formed on a horizontal floor. Based on the momentum conservation equation, the relationship of conjugate depths of the hydraulic jump may be expressed as (e.g., Peterka, 1958):

$$\frac{h_{mr}}{h_{jr}} = \frac{1}{2}\left(\sqrt{1+8F_{mr}^2}-1\right) \tag{1}$$

where h_{mr} and h_{jr} are the conjugate depths at the upstream and downstream ends of the hydraulic jump, respectively, and F_{mr} the Froude number at the upstream end of the hydraulic jump.

3. Experimental set-up

The facility is located at the Laboratório Nacional de Engenharia Civil (LNEC), in Lisbon (Figure 2). It was constructed in the framework of previous research (Matos, 1999, Meireles, 2004, Renna, 2004, Cardoso, 2007, Reis, 2015) and was slightly readapted for this experimental study. The facility includes a 2.96 m high (from crest to toe), 1.00 m wide, stepped chute, with a slope of 1V:0.75H, 8 cm high steps, and a 5.00 m long and 1.00 m wide stilling basin. The main geometric characteristics of the PKW spillway used in this research are expressed in Table 1.


(a) (b)

Figure 2 – Experimental set-up: (a) general downstream view; (b) upstream view of the PKW.

Table 1 – Main geometric characteristics of the PKW.

W_u	W	L	B	B_o/B_i	W_i	W_o	T_s	P	B_i	B_o	W_i/W_o	P/W_u	$2T_s/L$	L/W
(m)	(m)	(m)	(m)	(-)	(m)	(m)	(m)	(m)	(m)	(m)	(-)	(-)	(-)	(-)
0.39	1.00	4.29	0.67	1.00	0.22	0.15	0.01	0.20	0.13	0.13	1.50	0.51	0.01	4.29

In this work, USBR stilling basins type I and III were used. A scheme of the type III stilling basin is shown in Figure 3. The appurtenances were identical to those used in previous research conducted in the LNEC facility (*e.g.*, Meireles et al., 2010, Sun, 2011). Therein chute blocks were found to be dispensable for stilling basins downstream of stepped spillways. Baffle blocks and an end sill were used herein; they were placed at a distance of 32.5 and 88.5 cm downstream of the last step of the stepped spillway, respectively.

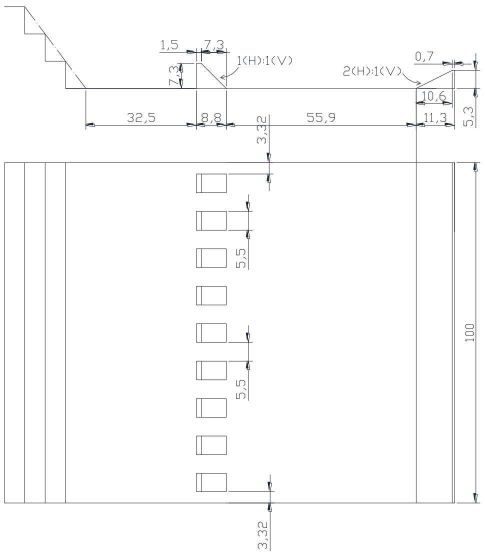


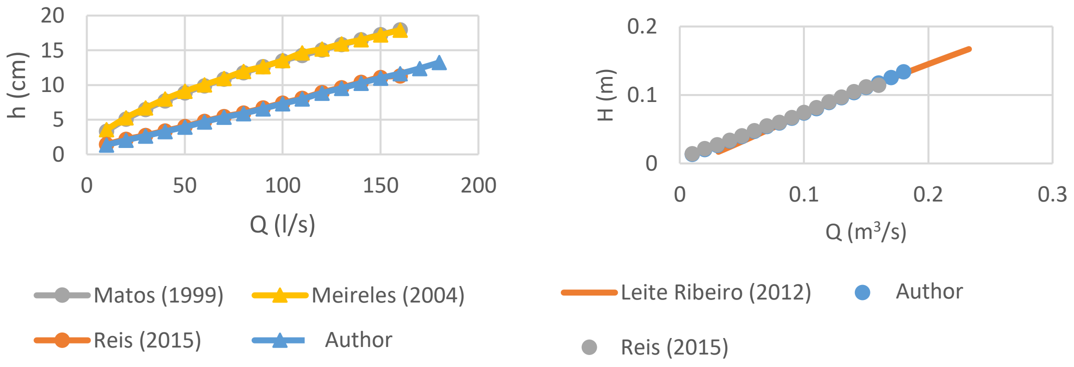
Figure 3 – USBR type III stilling basin used in the present research (adapted from Meireles, 2011).

4. Results

4.1 Rating curve

For the rating curve, discharges ranking from 10 to 180 l/s were tested. The results were compared with those obtained for PKW (Reis, 2015) and for WES type weirs (Matos, 1999, Meireles, 2004), Figure 4 shows that the PKW is much more efficient than the WES weir, as found in previous studies. For an identical flow depth above crest, the PKW allows a flow rate up to two to three times larger than that of the WES weir.

Figure 5 shows the results obtained in this study, along with those computed from the method proposed by Leite Ribeiro et al. (2012). As noted in Reis (2015), their method fits well to the data, except for small flow rates.



(a) (b)

Figure 4 – Rating curve: (a) data for PKW versus WES weirs at the LNEC chute; (b) PKW data at the LNEC chute versus method proposed by Leite Ribeiro et al. (2012).

4.2 Stilling basin

Experimental data were collected along the stilling basin for discharges ranging from 80 l/s to 180 l/s. Piezometric taps were installed on the stilling basin, along the basin (coordinate s, with origin at the spillway toe), and crosswise (coordinate L, from the left wall), immediately downstream of the stepped spillway, in the impact region of the flow on the basin, in three different alignments. All these taps were connected to a panel to acquire the pressure heads and their exact location can be found in Pinto (2017). In this paper, only results for the design discharge of the basin with appurtenances (Q = 180 l/s) are shown.

For all the tested discharges, the Froude number at the upstream end of the hydraulic jump varied between 4.5 and 6.0, corresponding to a stable hydraulic jump, according to Peterka (1958). For each discharge, the upstream end of the hydraulic jump was located in four different locations by changing the gate opening at the downstream end of the basin (Figure 5). Results for the third position, for which the hydraulic jump starts at the impact point of the flow in the stilling basin, are shown herein.

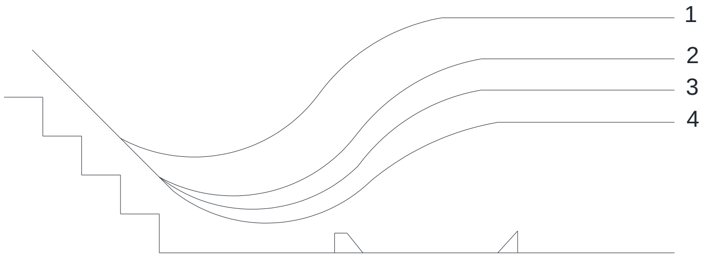


Figure 5 – Stilling basin: scheme of the location of the upstream end of the hydraulic jump.

The maximum piezometric heads were verified in the second alignment (s = 0.12 m), corresponding approximately to the section with minimum flow depth caused by the abrupt slope change. It is also in this alignment that a larger fluctuation of piezometric heads occur, in comparison with those in the first (s = 0.06 m) and third (s = 0.21 m) alignments.

Figures 6 and 7 illustrate the piezometric heads in the stilling basin without or with appurtenances, respectively, for Q = 180 l/s. The results show that the piezometric head is not influenced by the presence of the appurtenances, being mostly a function of the alignment.

Figure 8 shows the piezometric heads and the flow depths along the stilling basin with and without appurtenances, for Q=180 l/s. The results show that the maximum piezometric head is approximately 1.5 times larger than the piezometric head at the downstream end of the hydraulic jump, for both cases. The piezometric head and flow depth at the downstream end of the jump are smaller for the basin with appurtenances, as expected, due to the increased energy dissipation in such type of basin.

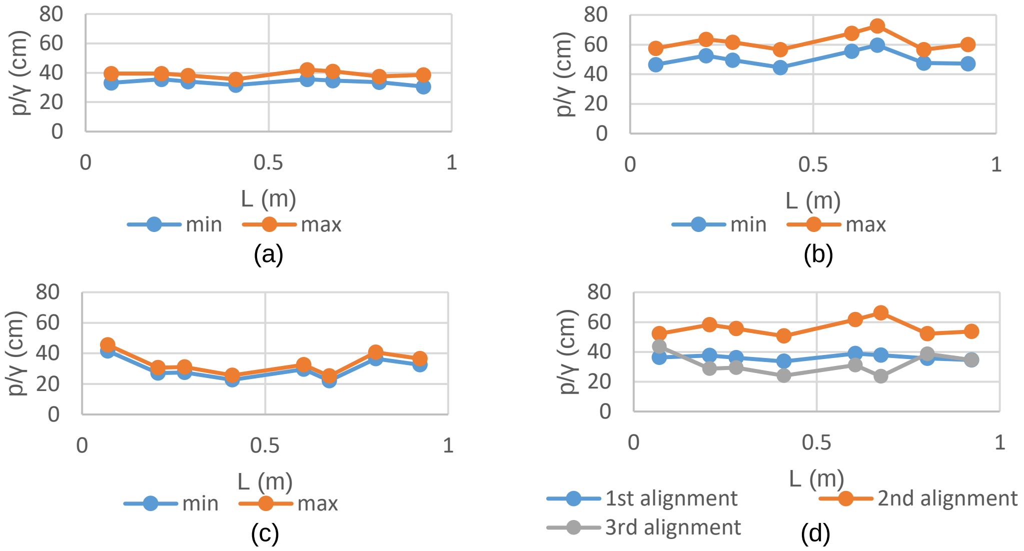


Figure 6 – Piezometric heads in the stilling basin without appurtenances in position 3 of the upstream end of the hydraulic jump, for Q=180 l/s: (a) 1st alignment; (b) 2nd alignment; (c) 3rd alignment; (d) mean values.

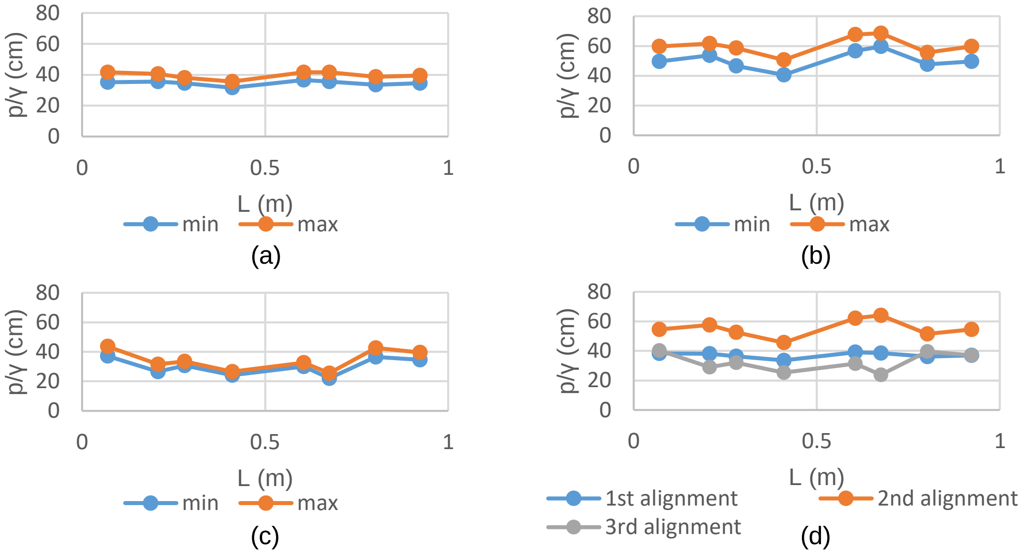


Figure 7 - Piezometric heads in the stilling basin with appurtenances in position 3 of the upstream end of the hydraulic jump, for Q=180 l/s: (a) 1st alignment; (b) 2nd alignment; (c) 3rd alignment; (d) mean values.

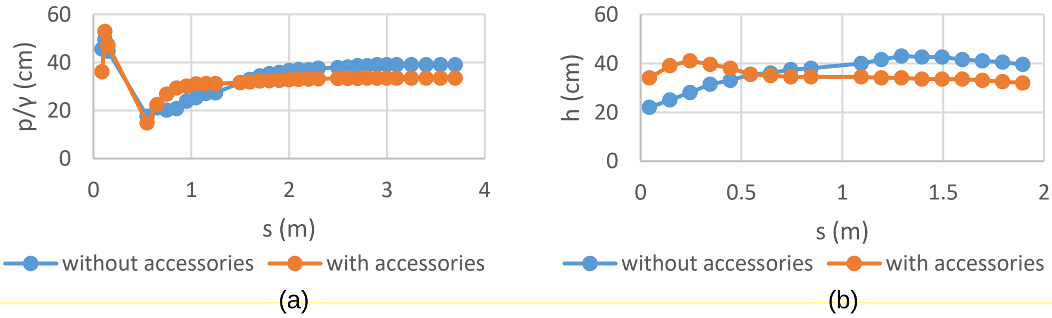


Figure 8 – Flow properties in the stilling basin with and without appurtenances, for Q=180 l/s: (a) piezometric head; (b) flow depth.

4.3 Energy dissipation

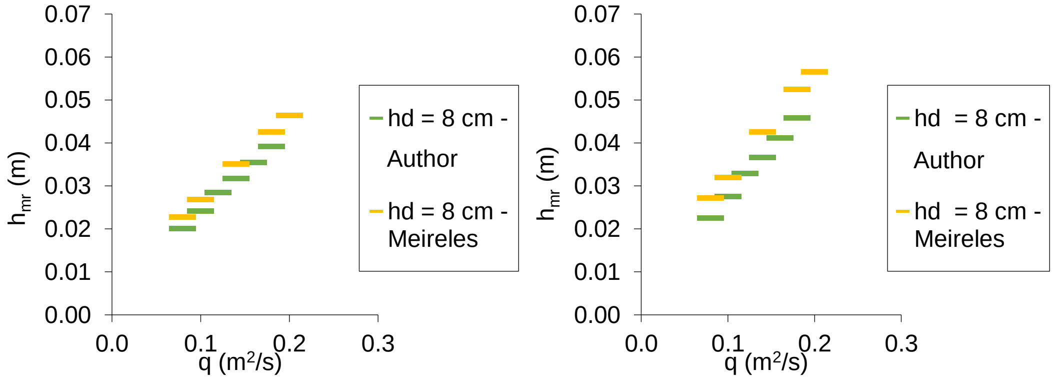
The specific energy at the spillway toe (residual specific energy) can be estimated from the flow conditions at the downstream end of the hydraulic jump formed at the spillway toe, as in previous studies (eg, Diez-Cascon et al., 1991, Tozzi 1992, 1994, Pegram et al., 1999, Povh and Tozzi 2003), and the subsequent application of the equation of conservation of momentum to determine the conjugate (supercritical) equivalent clear water depth at the upstream end of the hydraulic jump.

When applying the momentum conservation equation it is commonly accepted the hypothesis of hydrostatic pressure distribution at the upstream section of the hydraulic jump, which is a simplification. By analogy with results obtained downstream of a conventional chute, Tozzi (1992) considered that such simplification would not be valid. Identical conclusion was found by other authors on stepped spillways (e.g., Meireles, 2004).

The equivalent clear water depth and the specific energy at the upstream end of the hydraulic jump were then estimated from two approaches:

- Hypothesis of hydrostatic pressure distribution at the upstream end of the hydraulic jump - Hypothesis A;
- Hypothesis of linear pressure distribution at the upstream end of the hydraulic jump, obtained from the mean transverse values of the piezometric head in the second alignment of the stilling basin floor - Hypothesis B.

In Figure 9, results from both approaches are presented for the equivalent clear water depth, and compared to those obtained by Meireles (2004) in a stilling basin downstream of a stepped spillway with a WES profile. Even though the trend is very similar, smaller values of the equivalent clear water depth were obtained in the present study, with a PKW weir. Mean relative differences of 9% and 13% were obtained when comparing results of the present study against those of Meireles (2004), for hypothesis A and B, respectively.

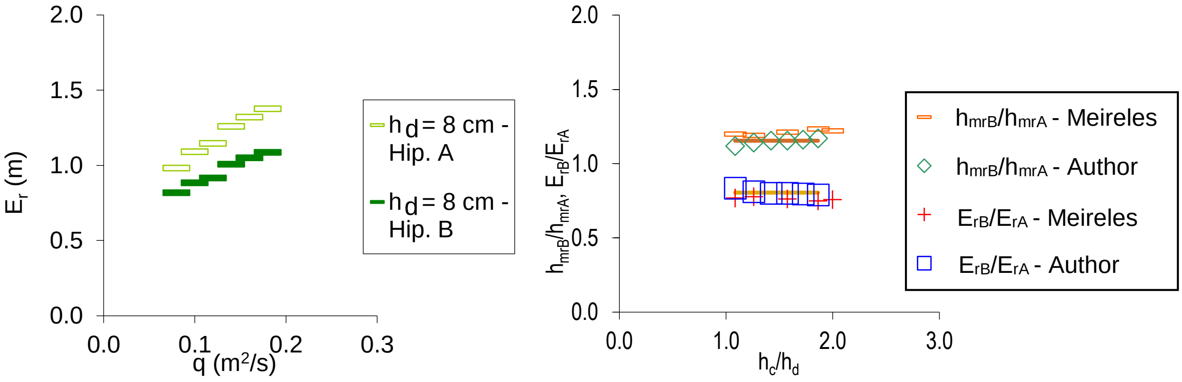


(a) (b)

Figure 9 – Conjugate depths at the upstream end of the hydraulic jump in the stilling basin without appurtenances: (a) hypothesis A; (b) hypothesis B.

In Figure 10, the influence of considering hypothesis A or B on the equivalent clear water depth and the specific energy at the upstream end of the hydraulic jump (residual specific energy) is shown. Similarly to the findings of Meireles (2004), hypothesis A leads to an underestimation of the equivalent clear water depth and an overestimation of the specific energy, at the upstream end of the hydraulic jump. Hence hypothesis A yields conservative results with regard to the residual specific energy.

The equivalent clear water depth and residual specific energy ratios (h_{mrB}/h_{mrA} ; E_{mrB}/E_{mrA}) were found to be practically independent of the relative critical depth h_c/h_d, as also found in Meireles (2004).



(a) (b)

Figure 10 – Influence of considering hypothesis A or B on the flow properties at the upstream end of the hydraulic jump: (a) specific energy; (b) equivalent clear water depth and specific energy.

The following results were found to fit well to the present study:

$$\frac{h_{mrB}}{h_{mrA}} = 1.16 \qquad (2)$$

$$\frac{E_{rB}}{E_{rA}} = 0.80 \qquad (3)$$

The dimensionless residual specific energy given by E_r/h_c in function of the relative dam height (H_d/h_c), are presented in Figures 11 and 12, respectively for hypothesis A and B on the stilling basin without appurtenances. The results are compared to those obtained by Matos (1999) and/or Meireles (2004), on identical flume except the ogee type (WES). Slightly larger values of the residual specific energy were obtained in the present study (PKW), for identical relative dam height.

For both hypothesis A and B, the dimensionless specific residual energy varies almost linearly with the relative dam height. The following regression equations were found to fit well to the data:

Hypothesis A (Figure 11):

$$E_r/h_c = 0.139\ H_d/h_c + 4.744,\ R^2 = 0.981\ \text{(Author)} \qquad (4)$$

$$E_r/h_c = 0.103\ H_d/h_c + 4.484,\ R^2 = 0.759\ \text{(Matos and Meireles)} \qquad (5)$$

Hypothesis B (Figure 12):

$$E_r/h_c = 0.147\ H_d/h_c + 4.431,\ R^2 = 0.982\ \text{(Author)} \qquad (6)$$

$$E_r/h_c = 0.086\ H_d/h_c + 4.351,\ R^2 = 0.985\ \text{(Meireles)} \qquad (7)$$

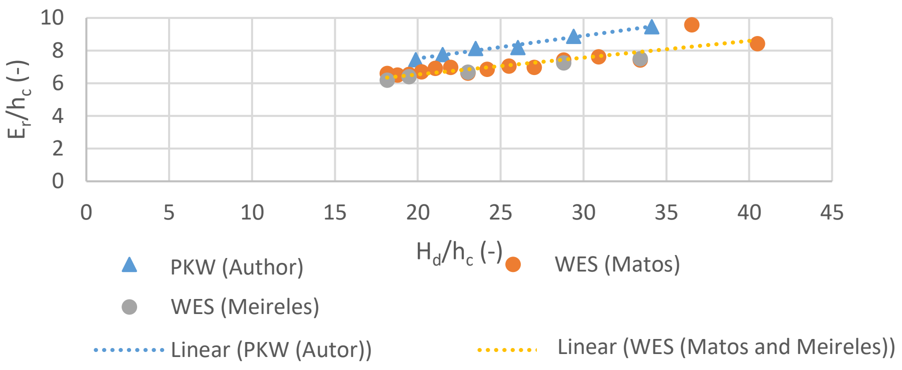


Figure 11 – Dimensionless residual specific energy in function of the relative dam height for hypothesis A, on the stilling basin without appurtenances.

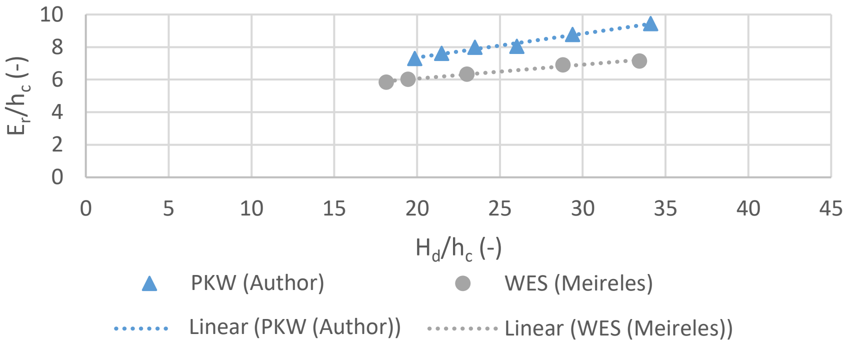


Figure 12 – Dimensionless residual specific energy in function of the relative dam height for hypothesis B, on the stilling basin without appurtenances.

Regarding PKW type weirs, the results of Figure 13 show an overall trend of decrease of the dimensionless residual specific energy E_r/E_{max} with the relative dam height H_d/h_c. For small values of H_d/h_c (~ 20), the results are quite close, whereas for higher values of H_d/h_c (~ 25-35), larger differences are observed. It should be noted that the geometry of the PKW type weir has an influence on the energy dissipation, as evidenced by the results of Silvestri (2012) for the PKW1 and PKW2 weirs.

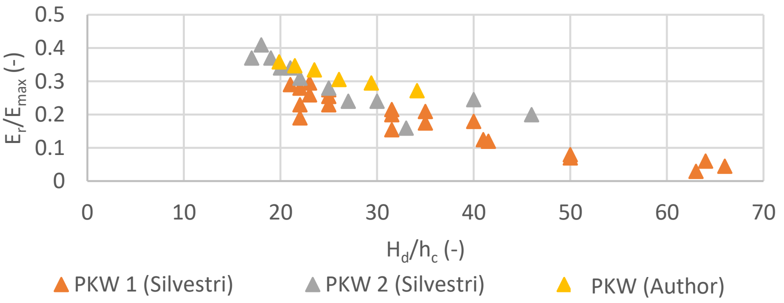


Figure 13 – Dimensionless residual specific energy in function of the relative dam height for hypothesis A, on the stilling basin without appurtenances

5. Conclusions

The main purpose of the present study was to provide a contribution to the estimation of the flow properties at the downstream end of a stepped spillway with a Piano Key Weir (PKW).

The following conclusions can be drawn from this experimental study:

- The rating curve of the PKW type weir is nearly linear, being much more efficient than that of a WES type weir; the empirical approach developed by Leite Ribeiro et al. (2012) was found to fit well to the head-discharge data acquired in the present investigation, similarly to the findings by Reis (2015).
- The piezometric heads in the section immediately upstream of the hydraulic jump are much larger than those based on the hydrostatic pressure distribution approach, which is in accordance to the conclusions of previous studies, namely Meireles (2004), Cardoso (2007) and Reis (2015).
- The values of the equivalent clear water depth obtained in the present study, with a PKW weir, are in average 9% and 13% lower than those obtained by Meireles (2004) with a WES ogee, for hypothesis A and B, respectively.
- The equivalent clear water depth and the specific energy ratios at the upstream end of the hydraulic jump were found to be practically independent of the relative critical depth, similarly to obtained by Meireles (2004) with a WES ogee.
- Slightly larger values of the residual specific energy were obtained in the present study (PKW), for identical relative dam height, in relation to those obtained by Matos and Meireles (2004) with an WES ogee.
- The dimensionless residual specific energy E_r/h_c varies practically linearly with H_d/h_c, for the analysed flow range.
- The dimensionless residual specific energy E_r/E_{max} obtained in this study is close to that presented by Silvestri (2012), for stepped spillways with PKW type weirs, for small values of H_d/h_c ($H_d/h_c \sim 20$); it is, however, larger for higher H_d/h_c (~25-35) values. Nevertheless, the decreasing trend of E_r/E_{max} with H_d/h_c is analogous.

Acknowledgements

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