River Flow 2016 – Constantinescu, Garcia & Hanes (Eds)

Experimental results on the physical model of an USBR type II stilling basin

O. Fecarotta, A. Carravetta, G. Del Giudice & R. Padulano
Department of Civil, Architectural and Environmental Engineering (DICEA), University of Naples "Federico II", Napoli, Italia

A. Brasca & M. Pontillo
Studio Ing. Pietrangeli s.r.l., Roma, Italia

ABSTRACT: The present paper describes the experimental campaign carried on the physical model of the spillway of Lower Diamphwe Dam (Malawi), which is provided with a USBR type II stilling basin. Stilling basins are used in order to reduce the excessive kinetic energy of flowing water downstream of spillways. Specifically, a USBR type II basin is provided with blocks at the end of the chute and with a confining dentated sill; these appurtenances allow to dissipate excess energy with high efficiency. The study focuses on the hydraulic behavior of the stilling basin; tests were carried on for different values of incoming discharge and downstream water depth. Results show the dissipation efficiency of the stilling basin in terms of pressure fluctuation and the variability of the jump type with the hydraulic characteristics of the incoming and the downstream flow depths.

1 INTRODUCTION

Spillways are provided in storage and detention dams to release surplus water or floodwater that cannot be contained in the allotted storage space, and for diversion dams to bypass flows exceeding those turned into the diversion system. Ordinarily, the excess is drawn from the top of the reservoir and conveyed through a constructed waterway back to the river or to some natural drainage channel (USBR 1987).

In order to reduce the excess kinetic energy of flowing water downstream of the spillway, stilling basins are used (Alikhani et al. 2010, Tiwari & Goel 2014). In a stilling basin excess energy is converted into heat, spray and sound by means of a turbulent vortex structure induced by the jump. Such a structure must be designed economically in terms of length, tailwater level, scour and cavitation (Vischer & Hager 1999).

Various types of recommended stilling basin used for evacuation systems are USBR stilling basin (Bradley & Peterka 1957), Manifold stilling basin (Fiala & Albertson 1963) Contra Costa energy dissipator (Keim 1962), USU energy dissipator (Flammer et al. 1970), counter current energy dissipator (Vollmer & Khader 1971), Garde energy dissipator (Garde et al. 1986), Verma energy dissipator (Verma & Goel 2000), Mahakaal stilling basin (Tiwari et al. 2011), etc.

The influence of the geometry of stilling basin on the hydraulic characteristics of the flow has been studied by several researchers. Ohtsu et al. (1991) and Hager and Li (1992) described the effect of a continuous end sill on the hydraulic jump, while Habibzadeh et al. (2011) studied the dissipation efficiency of baffle blocks when a submerged jump occurs.

This paper describes the experimental campaign performed on the physical model of Lower Diamphwe Dam (Malawi), which is provided with an uncontrolled spillway and a USBR type II stilling basin. The USBR type II basin is provided with blocks at the end of the chute and a dentated sill at the end of the basin (Fig. 1). The aim of the paper consists in the study of its hydraulic behavior, which has been poorly investigated so far, to the Authors' knowledge. Measurements of pressure fluctuation upstream and downstream of the dentated sill were

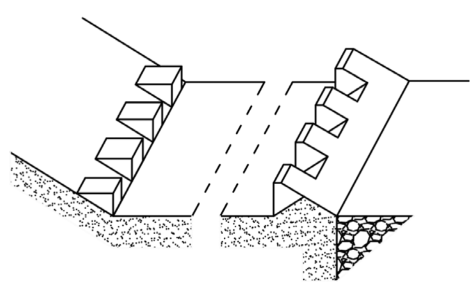

Figure 1. USBR Type II stilling basin.

performed and the pressure fluctuation were related to the dissipation efficiency of the dentated sill. Furthermore, the tests were performed with variable discharge and tailwater level in order to relate the jump type with the hydraulic characteristics of both incoming and outcoming flows.

2 REVIEW OF LITERATURE

2.1 *Hydraulic features*

Given the type of USBR stilling basin described in the present paper, the state-of-the-art just provides for general understanding about hydraulic behavior of stilling basins and design of experiments, since literature experimental analyses typically concern different sill geometries (vertical continuous sill, baffle block sill). Specifically, papers by Ohtsu et al. (1991) and Hager and Li (1992) gave a fundamental contribution as concerns classification of jump types and non-dimensional variables explaining the hydraulic behavior of the basin, which usually involve Classic Hydraulic Jump (CHJ) variables. Hydraulic jumps induced or constrained by some kind of appurtenances are referred to as "forced" as opposed to CHJ.

For an approach discharge Q subject to a hydraulic hump, h_1 is defined as the water depth at the jump toe (Fig. 2), and F_1 is the corresponding Froude number in supercritical flow. For a CHJ, h^*_2 is usually denoted as the sequent depth, and the sequent depth ratio $Y^* = h^*_2/h_1$ is

$$Y^* = \frac{1}{2}\left[\left(1+8F_1^2\right)^{1/2} - 1\right] \tag{1}$$

The length of the jump is very difficult to measure; different definitions have been proposed (Khatsuria 2005), all measured from the toe or front of the jump, such as the jump length L^*_j, measured up to the section of maximum depth; the roller length L^*_r, ending at the surface stagnation point and indicating the limit between the backward and forward flow; the erosion length L^*_e, ending at a section where no bottom erosion occurs. For a CHJ, Hager & Li (1992) propose.

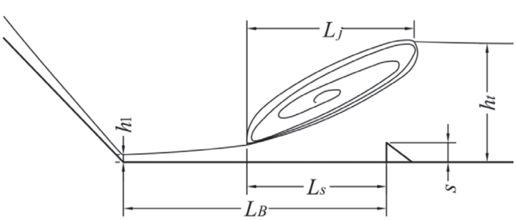

Figure 2. Variables in a USBR Type II stilling basin.

$$\frac{L_r^*}{h_1} = -12 + 160 \cdot \tanh\left(\frac{F_1}{20}\right) \tag{2}$$

$$\frac{L_j^*}{h_1} = 220 \cdot \tanh\left(\frac{F_1 - 2}{22}\right) \tag{3}$$

whereas Ohtsu et al. (1991) and Vischer & Hager (1999) propose

$$\frac{L_r^*}{h_2^*} = 4.5 \quad \frac{L_j^*}{h_2^*} = 5.5 \div 6 \tag{4}$$

When a forced jump occurs, the subcritical flow depth is fixed by a downstream control to a value h_t (tailwater depth) which is generally different from h_2^*. This implies that the hydraulic jump shifts downstream (if $h_t < h_2^*$) or upstream (if $h_t > h_2^*$) and Eqs. (1–4) must be recomputed; for this reason, the tailwater depth—discharge relation must be carefully known (Vischer & Hager 1999). If $h_t >> h_2^*$, hydraulic jump may have no room to develop (submerged jump): the water profile is horizontal and turbulence develops below the free surface.

However, in a confined stilling basin the jump displacement does not only depend on the difference between tailwater and sequent depth but also on the specific appurtenance limiting the basin, that could be, for instance, a continuous vertical or sloping sill or alternate blocks.

Basing on the experimental analysis of a stilling basin confined by a vertical continuous sill, Ohtsu et al. (1991) give a different classification of hydraulic jumps, describing the following jump types:

- Type I, with the flow condition upstream of the sill influenced by the tailwater depth;
- Type II, with the flow condition upstream of the sill not influenced by the tailwater depth;
- Spray condition, with the supercritical flow impinging directly on the sill.

Submerged jumps are not considered. For Type I, the tailwater reduction $Y = h_t/h_1$ is expressed as a function of relative sill height and approach Froude number with the following equation

$$Y = Y^*\left[1 - 1.9F_1 \cdot \frac{s}{L_s}\right]^2 \tag{5}$$

whereas for Type II flow conditions are independent on h_t, and the governing equation relates the relative sill height and approach Froude number:

$$\frac{s}{h_1} = -1.05\left(F_1 - 2\right)\left(1 - \frac{L_s}{L_j^*}\right) + 1.08F_1 - 1.56 \tag{6}$$

The sill height marking the passage from Type II to Spray jump is given by the following expression

$$\frac{s_C}{h_1} = -0.227F_1 + 0.349 \tag{7}$$

Empirical considerations about basin and roller length are reported in Ohtsu (1981) where these variables are related to the head loss $H_L = H_1 - H_t$.

$$\log\left(\frac{L_B}{H_L}\right) = 1.72 - 1.71\left(\frac{H_L}{H_1}\right) \tag{8}$$

$$\log\left(\frac{L_r + L_s}{H_L}\right) = 1.40 - 1.71\left(\frac{H_L}{H_1}\right) \tag{9}$$

For non-submerged jumps, according to the relative position of the roller end and the confining appurtenance consisting of a vertical continuous sill, Hager & Li (1992) classify:

- A-jump, with end of the roller before or over the confining appurtenance;
- B-jump, with the roller extending beyond the appurtenance with a small standing wave;
- Minimum B-jump (B_m), same as B-jump but with a definite second surface roller downstream of the appurtenance;
- C-jump, with a downstream standing wave involving considerable pulsation and development of spray;
- Spray or wave type jump with supercritical flow over the appurtenance and unacceptable energy dissipation.

For a fixed approach Froude number, jump type evolves from A-jump to Spray for decreasing tailwater with a fixed sill height, or for increasing sill height with a fixed tailwater level. The C-jump and Spray are usually considered as ineffective in terms of energy dissipation and are not recommended for stilling basins (Vischer & Hager 1999). Consequently, Hager & Li (1992) provide for a limit relative height of the sill s/h_1

$$\frac{s}{h_1} = \left[C_L \cdot \left(1 - \frac{L_s}{L_r^*}\right)\right]^{-2} \tag{10}$$

where s is the height of the sill and L_s is the distance between the sill and the jump toe (Fig. 1); $C_L = 4$ for the transition from A- to B-jump, and $C_L = 2.5$ between B- and B_m-jump. Given that the basin length L_B must be at least equal to the distance between the jump toe and the end of bottom roller, the Authors also give

$$\frac{L_B}{L_r^*} = \frac{4}{3}\left[1 - 0.6\left(\frac{s}{h_1}\right)^{\frac{1}{3}}\left(1 - \frac{L_s}{L_r^*}\right)\right] \tag{11}$$

with all the symbols previously defined. Finally, Hager & Li (1992) propose an estimate of the ratio of sequent depths $Y = h_t/h_1$ based on the concept that a forced hydraulic jump is a distorted CHJ. Specifically, given $Y = Y^* - \Delta Y_f - \Delta Y_s$, where ΔY_f is the effect of wall friction and ΔY_s is the effect of the sill, for $L_s/L^*_r > 0.5$ experimental results provide

$$\Delta Y_s = 0.7\left(\frac{s}{h_1}\right)^{0.7} + 3\frac{s}{h_1}\left(1 - \frac{L_s}{L_r^*}\right)^2 \tag{12}$$

2.2 *Pressure fluctuations*

In a stilling basin the pressure regime undergoes severe low-frequency fluctuations due to large-scale turbulence structures developing within the basin. Generally, such fluctuations are treated as random variations, so that their analysis concerns probability distribution and statistical parameters such as mean, standard deviation or RMS, skewness and kurtosis. A statistical parameter usually adopted for pressure analysis is the pressure coefficient C_p^I (Vischer & Hager 1999; Toso & Bowers 1988), which compares pressure RMS or standard deviation σ with the inflow velocity head:

$$C_p^I = \frac{\sigma}{V_1^2/2g} \tag{13}$$

Mean pressures P_m and both negative and positive fluctuations from the mean ΔP^+ and ΔP^- can be similarly expressed:

$$C_p = \frac{P_m}{V_1^2/2g} \quad C_p^{+/-} = \frac{\Delta P^{+/-}}{V_1^2/2g} \tag{14}$$

Estimating the magnitude of extreme pressures on the basin floor is of utmost importance to understand about the possible uplift of the chute or basin slab, which could cause severe damage to the structure (Fiorotto & Caroni 2014). According to a detailed study proposed by Toso & Bowers (1988) concerning unconfined basins, extreme pressure fluctuation depends on the approach Froude number, on the boundary layer development and on the inflow angle. Also, maximum positive and negative fluctuations take place at different distances from the chute. For basins confined by baffle appurtenances, turbulence is not completely contained within the basin and small fluctuations can be observed downstream (Toso & Bowers 1988).

3 PHYSICAL MODEL

The behavior of the stilling basin of Lower Diamphwe Multipurpose Dam has been studied by means of an experimental investigation on an acrylic glass scale model. It is well known that scale effects can occur in spillway and stilling basin modelling according to Froude similitude (Novak et al. 2010, Pfister & Chanson 2012). The upstream basin is significantly deep and the shape of the upstream basin is mostly symmetrical; thus, a planar investigation of the phenomena was performed.

In order to limit scale effects a 1:40 scale model for the whole dam was built. The model consists of a detention tank that receives the water supply, a filling tank governing the water head above the spillway crest (detention and filling tanks are separated by a filtering wall) and an acrylic glass flume simulating stilling basin and downstream channel (Fig. 3).

In order to investigate about the influence of the tailwater head—discharge relation, downstream water head can be changed by means of a moving flap (Fig. 4). The model is also equipped with eight pressure transducers measuring the dynamic pressure at the bottom of the basin and of the river in several measurement points (pressure taps can be seen in Fig. 5). A point gage was used to measure water levels and an orifice plate for the monitoring of approach discharge.

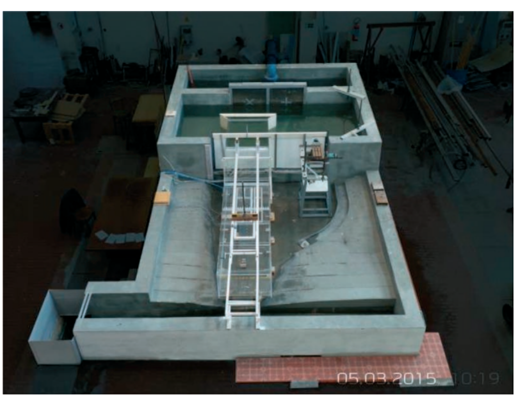

Figure 3. Model setup (concrete tank and acrylic glass flume).

Figure 4. Moving flap enables changing tailwater level.

Figure 5. Pressure taps with transducers under the basin floor.

4 MEASUREMENTS

The scope of the experimental analysis is to study the behavior of the stilling basin and its dissipation efficiency. The model simulates the planar flow on the spillway, in the stilling basin and in a portion of the downstream river (about 68 meters in the real scale). Experiments were performed for 11 values of the inflow discharge (Table 1). In order to investigate the influence of the downstream flow on the behavior of the basin, several values of the tailwater level h_t were tested for each discharge value (Table 1 shows maximum and minimum tailwater depth for each tested discharge).

Preliminary results of the experimental campaign concerned the classification of jump types according to the classification proposed by Hager & Li (1992). For a fixed discharge, jump types are shown in Figure 6 for decreasing tailwater level (and, consequently, of distance L_s between blocks and jump toe).

Pictures were digitalized to obtain water profiles for all experimental discharges and tailwater levels. This allowed to obtain systematic information about the positions of jump toe and end from the chute, distance L_s between the jump toe and the blocks and jump length L_j. The end of the jump is included within the basin only for A-jumps; distance between the jump toe and the chute is negative for submerged jumps. As a first attempt, results were represented in Figure 7. For a fixed discharge, h_1 and h_2^* are evaluated and h_t is varied by means of

Table 1. Experimental variables.

$Q_{real\ scale}$ [m³/s]	Q_{model} [l/s]	F_1	H_1 [cm]	h_t max [cm]	h_t min [cm]
20.85	10.3	19.89	0.336	14.83	6.06
23.88	11.8	18.64	0.384	15.68	5.25
26.11	12.9	17.87	0.419	16.25	5.33
28.74	14.2	17.07	0.460	16.89	5.04
31.98	15.8	16.23	0.511	17.6	5.06
36.02	17.8	15.35	0.575	18.4	5.20
39.06	19.3	14.78	0.622	19.02	5.24
46.55	23	13.61	0.739	20.36	7.23
54.04	26.7	12.70	0.855	21.56	8.35
93.30	46.1	9.86	1.455	25.04	12.92
132.36	65.4	8.41	2.044	29.97	16.24

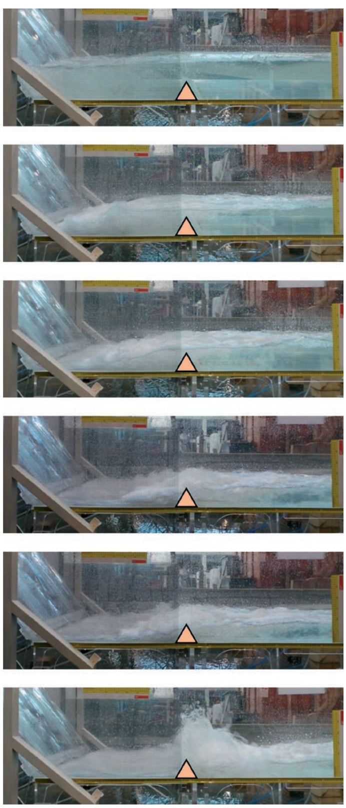

Figure 6. Submerged jump; A-, B-, B_m-, C- and Spray jumps (sill highlighted) for $Q = 26.7$ l/s.

the moving flap; for minimum h_t values Spray jumps are experienced, then jump types move from C- to A- for increasing tailwater; maximum experimental tailwater levels correspond to submerged jumps.

From Figure 7 it can be noted that the relation between Y/Y^* and Y is linear, and for low F_1 values smaller values of Y/Y^* can be obtained. Figure 8 shows the relation between L_s and Y for different jump types. It can be noted that for low Y values the toe of the jump is located near the confining blocks at the end of the stilling basin. For increasing Y the toe progressively shifts towards the end of chute moving from Spray to A-jumps, overcoming it when submerged jumps occur.

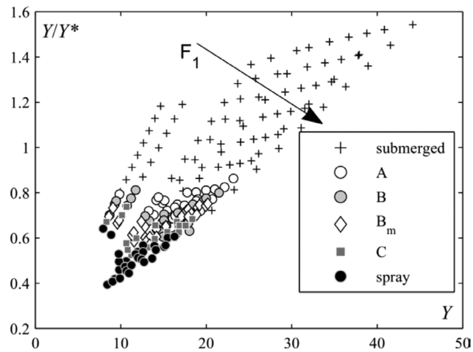

Figure 7. Submerged jump; A-, B-, Bm-, C- and Spray jumps.

Further elaborations of experimental results concerned the possible adoption of non-dimensional variables proposed by Ohtsu et al. (1991) and Hager & Li (1992) as an abacus with each jump type gathering in specific regions. Results are shown in Figures 9 and 10.

As can be seen in Figure 9, as the experimental campaign didn't involve sill height changing, for a fixed discharge the ratio s/h_1 is constant and jump type vertically moves from Spray to submerged with increasing tailwater level. Such an abacus is particularly adapt for highlighting the existence region of submerged jumps, whereas remaining jumps can't be easily distinguished.

In Figure 10 the Hager & Li (1992) abacus is shown: for a fixed discharge, L_r^* and Y^* are known and jump types evolve from submerged to Spray-jumps for decreasing L_s and increasing Y.

In order to obtain information about the dissipation efficiency of the stilling basin, pressure fluctuations were measured inside and outside the stilling basin. Figure 11 shows the pressure coefficient C_p^I measuring the standard deviation of fluctuations as a function of x/L_B, being x the distance of each pressure tap from the end of the chute ($x/L_B = 1$ indicates sill position), for fixed approach Froude number and for different tailwater levels. For all the jump types, except from the Spray jump, pressure fluctuations significantly decrease downstream of the dentated sill, showing that most of the turbulence is included within the stilling basin. Both the upstream and downstream C_p^I values increase moving from the submerged to the C-jump, because of the additional turbulent structures induced by the sill, especially for B_m- and

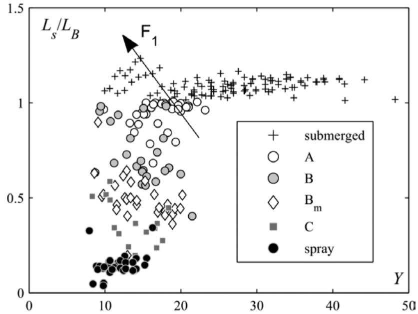

Figure 8. Submerged jump; A-, B-, Bm-, C- and Spray jumps.

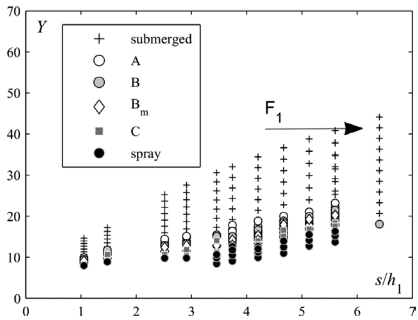

Figure 9. Abacus by Ohtsu et al. (1991).

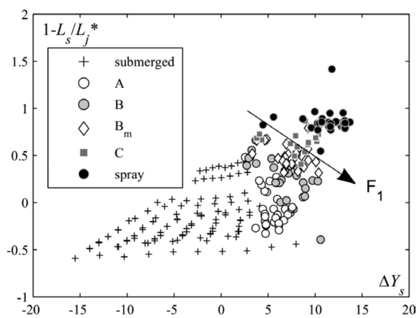

Figure 10. Abacus by Hager & Li (1992).

C-jumps. For Spray jumps, a significantly larger C_p^I can be observed above the sill and downstream, because of the flow impingement on the sill.

Figure 12 shows mean pressures for the same tailwater levels, roughly reproducing the water surface profile. Submerged jump is the only case when mean pressures inside the basin are higher than outside. For A- and B-jumps pressures are comparable inside and outside the basin, whereas for the remaining jumps pressures outside the basin are higher than inside.

Figures 13 and 14 show the values of maximum and minimum pressure deviations from the mean.

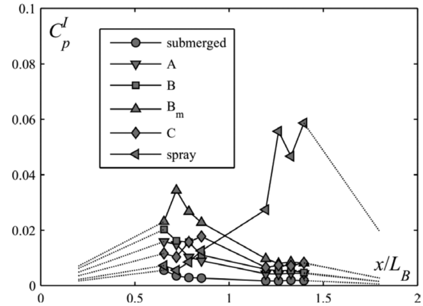

Figure 11. Standard deviation of pressure fluctuations along the stilling basin ($x/L_B = 1$ marks the sill). See Figure 12 for tailwater levels. Grey lines represent assumed trends.

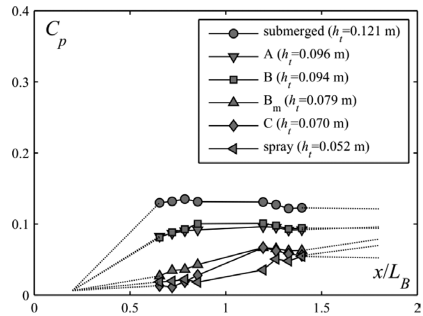

Figure 12. Mean pressures along the stilling basin ($x/L_B = 1$ marks the sill). Grey lines represent assumed trends.

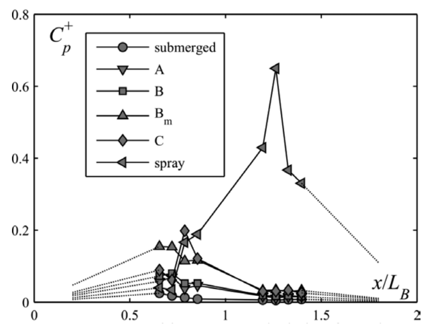

Figure 13. Extreme positive pressure deviation from the mean along the stilling basin ($x/L_B = 1$ marks the sill). See Figure 12 for tailwater levels. Grey lines represent assumed trends.

In both cases the trend is similar to Figure 11, with lower values of fluctuation magnitude occurring downstream of the sill for all jump types but Spray jump. Also, for submerged, A- and B-jumps the extreme C_p^- is higher than the extreme C_p^+ in accordance with Toso & Bowers (1988) whose study concerns an unconfined stilling basin. The difference between C_p^- and C_p^+ decreases from submerged to

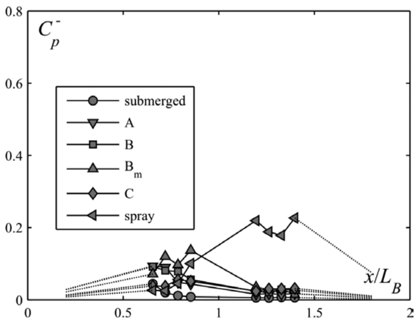

Figure 14. Extreme negative pressure deviation from the mean along the stilling basin ($x/L_B = 1$ marks the sill). See Figure 12 for tailwater levels. Grey lines represent assumed trends.

B-jump, becomes negative for B_m-jumps and keeps increasing in absolute value. For Spray jumps the most significant difference between extreme pressure deviations can be observed, with C_p^+ being about three times C_p.

5 CONCLUSIONS

An experimental campaign was undertaken on the 1:40 physical model of a USBR Type II stilling basin to understand about its hydraulic behavior and dissipation efficiency. As concerns the first issue, six jump types were found possible, namely submerged jumps and jump types from A- to Spray according to the classification by Hager & Li (1992). Hydraulic features of the stilling basin are highly dependent on jump types in terms of hydraulic jump appearance (length and position of the jump toe relative to the sill) and efficiency. Relative jump toe position was found to be dependent on the ratio of tailwater level to inflow depth. The latter is in turn dependent on the approach Froude number. A non-dimensional representation of results was attempted by means of the non-dimensional variables proposed by Ohtsu et al. (1991) and Hager & Li (1992). As concerns dissipation efficiency, some considerations were obtained by analyzing pressure fluctuations in different sections both inside and outside of the stilling basin. In addition to the dependence on the approach Froude number found in literature, a deep dependence of fluctuations was found on the jump types, with higher extreme pressures and not negligible residual fluctuations coupled with B_m-, C- and Spray jumps. Finally, the overall efficiency of the USBR Type II stilling basin is demonstrated by the highly satisfactory reduction of pressure fluctuations outside the basin for all the jump types but the Spray jump.

REFERENCES

Alikhani, A., Behrozi-Rad, R., & Fathi-Moghadam, M. 2010. Hydraulic jump in stilling basin with vertical end sill. *International Journal of Physical Sciences*, 5(1), 025–029.
Bradley, J.N., & Peterka, A.J. 1957. The hydraulic design of stilling basins: hydraulic jumps on a horizontal apron (basin i). *Journal of the Hydraulics Division*, 83(5), 1–24.
Fiala, G.R., & Albertson, M.L. 1963. Manifold stilling basin. *Transactions of the American Society of Civil Engineers*, 128(1), 428–453.
Fiorotto, V., & Caroni, E. 2014. Unsteady seepage applied to lining design in stilling basins. *Journal of Hydraulic Engineering*, 140(7), 1–9.
Flammer, G.H., Skogerboe, G.V., Wei, C.Y., & Rasheed, H. 1970. Closed Conduit to Open Channel Stilling Basin. *Journal of the Irrigation and Drainage Division*, 96(1), 1–10.
Garde, R.J., Saraf, P.D., & Dahigaonkar, D.J. 1986. Evolution of design of energy dissipator for pipe outlets. *Journal of Irrigation & Power*, 41(3), 145–154.
Habibzadeh, A., Wu, S., Ade, F., Rajaratnam, N., & Loewen, M.R. 2011. Exploratory study of submerged hydraulic jumps with blocks. *Journal of Hydraulic Engineering*, 137(6), 706–710.
Hager, W.H., & Li, D. 1992. Sill-controlled energy dissipator. *Journal of Hydraulic Research*, 30(2), 165–181.
Khatsuria, R.M. 2005. Hydraulics of spillways and energy dissipators, Marcel Dekker, NY.
Keim, S.R. 1962. The Contra Costa Energy Dissipator. *Journal of the Hydraulics Division*, 88(2), 109–122.
Novak, P., Guinot, V., Jeffrey, A., & Reeve D.E. 2010. *Hydraulic modeling: an introduction*. Spon Press, London.
Ohtsu, I. 1981. Forced hydraulic jump by a vertical sill. *Trans. JSCE, Hydraucli and Sanitary Engineering Division*, 13, 165–168.
Ohtsu, I., Yasuda, Y., & Yamanaka, Y. 1991. Drag on vertical sill of forced jump. *Journal of Hydraulic Research*, 29(1), 29–47.
Pfister, M., & chanson, H. 2012. Discussion of “Scale effects in physical hydraulic engineering models” by Valentin Heller. *Journal of Hydraulic Research*, 50(2), 244–246.
Tiwari, H.L., & Goel, A. 2014. Effect of end sill in the performance of stilling basin models. *American Journal of Civil Engineering and Architecture*, 2(2), 60–63.
Tiwari, H.L., Goel, A., & Gahlot, V.K. 2011. Experimental Study of Sill Controlled Stilling Basins for Pipe Outlet. *International Journal of Civil Engg. Research*, 2(2), 107–117.
Toso, J.W., & Bowers, C.E. 1988. Extreme pressures in hydraulic-jump stilling basins. *Journal of Hydraulic Engineering*, 114(8), 829–843.
USBR 1987. *Design of small dams*. A Water Resources Technical Publication. Washington: US Government Printing Office.
Verma, D.V.S., & Goel, A. 2000. Stilling basins for pipe outlets using wedge-shaped splitter block. *Journal of Irrigation and Drainage Engineering*, 126(3), 179–184.
Vischer, D.L., & Hager, W.H. 1999. *Dam Hydraulics*. John Wiley & Sons.
Vollmer, E., & Khader, M.H.A. 1971. Counter current energy dissipator for conduit outlets. *International Journal of Water Power*, 23(7), 260–263.