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Study of optimization of the Piano Key Weir

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ABSTRACT: Labyrinth weirs are adequate solution in dam rehabilitation projects when the storage and\or discharge capacity has to be increased. Piano key weirs (PKW) are particularly interesting due to their structure as well as their upstream and downstream flow conditions. PKW have a different geometrical shape than the classic labyrinth weirs. The keys are rectangular shaped with inclined key bottoms allowing the use of overhangs. Two different types of PKW were defined: Type A shows two overhangs, one upstream and one downstream. Type B does not have the downstream overhangs. Physical modelling tests have showed that the efficiency of Type B is higher than of Type A. The study reveals that flow on the PKW is influenced by different geometrical parameters. The dimensional analysis allowed the development of relations between discharge capacity and the shape of the PKW.

1 INTRODUCTION

Labyrinth weirs are interesting alternatives to reduce the risk of dam failure. They are often applied in dam rehabilitation projects when the storage and/or spillway capacity has to be increased. The Piano Key Weir (PKW) is a particularly interesting solution due to its rigid structure and its upstream and downstream flow conditions. The PKW was developed in 2003 (Lempérière & Ouamane 2003). Its geometry is different from the classical labyrinth weir. The keys are rectangular shaped and have an inclined bottom to favor the use of key overhangs. Two different types of PKW are distinguished (Ouamane & Lempérière 2006a, b): Type A is characterized by two overhang keys, one upstream and one downstream. Type B differs from Type A by the lack of the downstream overhangs. The physical modeling tests results obtained on Type B showed that discharge capacity is higher compared to Type A. The study focused on the optimization of PKW. It shows that flow depends on various geometric parameters, which characterize this particular type of spillway. The dimensional analysis of flow allowed the development of mathematical relationships, helpful for PKW design.

2 SYSTEM OF GEOMETRIC PIANO KEY WEIR

Lempérière and Ouamane (2003) mention the following main PKW characteristics:

- A rectangular arrangement of keys is similar to the keys of a piano;
- The alternatively placed inlet and outlet keys have downstream respectively upstream overhangs;
- Even on small platforms, considerable crest lengths can be achieved;
- The overhangs reduces the base width of the PKW;
- The surface of the side walls is reduced due to inclined keys.

3 EXPERIMENTAL SETUP

An upstream channel of a section of 0.75 m to 0.75 m and a length of 3.5 m supplies the squarely shaped basin. It is 3 m wide, 3 m long and 1.1 m deep. The upstream inlet of the basin is equipped

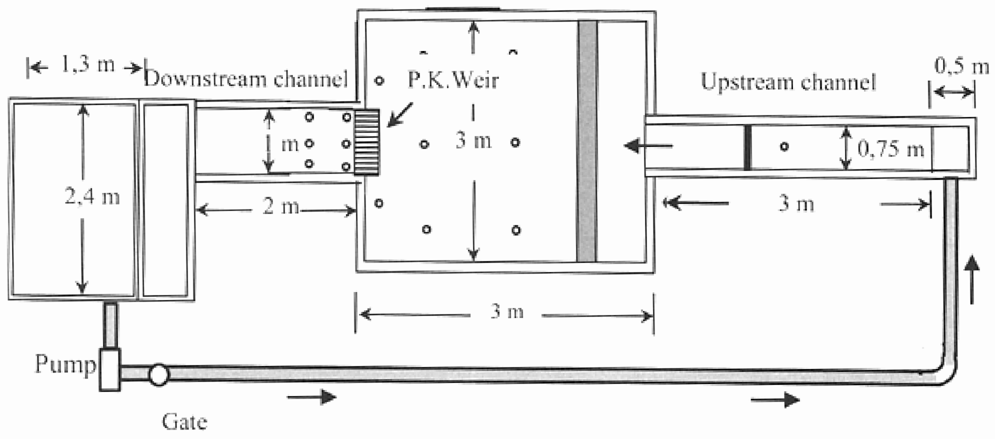

Figure 1. Plan view of the experimental device.

with a metal gate and a brick wall that provide uniform upstream flow conditions. A series of pressure taps is placed at different locations in the basin, to define the water column. The PKW models are installed at the outlet of basin. Downstream of the spillway, a 2 m long and 1 m wide channel is located.

4 RESULTS

The flow coefficient is derived from the universal equation that expresses the flow passes through a weir:

$$C_W = \frac{Q}{W\sqrt{2g}H^{3/2}} \tag{1}$$

where C_W = flow coefficient; Q = discharge; W = weir width; and H = upstream head.

The flow coefficient C_W can be defined by the measured flow Q and the upstream head H. It is suitable to represent the flow coefficient as a function of dimensionless parameters. The π theorem of Buckingham allows a dimensional analysis on the discharge capacity of Type B PKW. Following relationships could be developed:

$$\Pi_1 = Q/\sqrt{g}W_o^{5/2} \tag{2}$$

$$\Pi_2 = H/W_o \tag{3}$$

$$\Pi_3 = L/W_o \tag{4}$$

$$\Pi_4 = W/W_0 \tag{5}$$

$$\Pi_5 = P/W_o \tag{6}$$

$$\Pi_6 = W_i/W_o \tag{7}$$

where W_o = outlet key width; W_i = inlet key width; L = crest length; and P = total weir height.

By combining these parameters, the relationship is obtained:

$$C_W = f(H/P, L/W, W/P, W_i/W_o) \tag{8}$$

To better understand the effect of these dimensionless parameters on the flow of the Type B PKW, ten models were tested.

4.1 *Comparison between PKW model A and B*

A Type A (Fig. 2) and a Type B PKW (Fig. 3) have been tested in the test flume.

Table 1. Geometrical parameters of the tested PKW (W_u width of PKW unit, $n = L/W$).

Model	L [cm]	W [cm]	W_u [cm]	P [cm]	n [–]	W_i [cm]	W_o [cm]	B [cm]	L/W [–]	W_u/P [–]	W_i/W_o [–]
A	600	100	16.67	15	6	9	7.5	41	6	1.11	1.2
B01	600	100	16.67	15	6	9	7.5	41	6	1.11	1.2
B02	600	100	16.67	15	6	10	6.5	41	6	1.11	1.5
B03	400	100	25	15	4	15	10	41	4	1.67	1.5
B04	800	100	12.5	15	8	7.6	4.8	41	8	0.83	1.5
B05	600	100	16.67	15	6	6.6	9.9	41	6	1.11	0.7
B06	600	100	25	15	4	15	10	62.5	6	1.67	1.5
B07	400	100	25	20	4	15	10	41	4	1.25	1.5
B08	600	100	16.67	20	6	9	7.5	41	6	0.83	1.2
B09	400	100	25	25	4	15	10	41.2	4	1	1.5

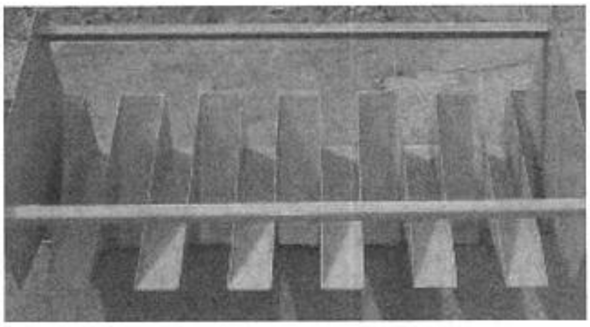

Figure 2. Model of PKW model A.

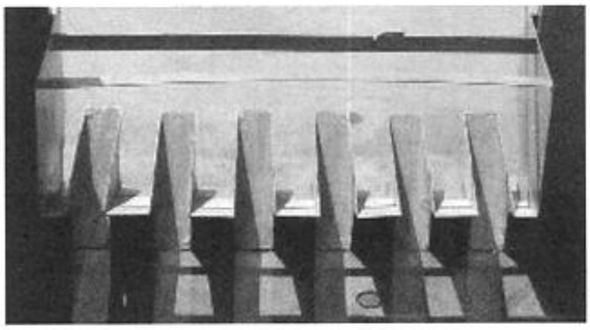

Figure 3. Model of PKW model B.

The test results show that Type B without downstream overhangs is an appropriate solution for high flow rates. Type A is a symmetric and therefore a very economical solution. Prefabricated elements can be used for construction. It is recommended to design the PKW without downstream overhangs if it is structurally stable during the periods when the level in the reservoir is lower than the threshold weir level.

4.2 *Influence of L/W ratio*

Two PKW with different L/W ratios were tested. Figure 5 shows that the discharge capacity can be significantly increased by increasing L/W ratio from 4 to 6. This increase is about 15% for $H/P = 0.2$ and 8% for medium heads of $H/P = 0.4$.

4.3 *Influence of W/P ratio*

Three models of $L/W = 4$ have been tested by models B03, B07 and B09 (Fig. 6). The difference between the curves of model B03 ($W/P = 1.67$) and B07 ($W/P = 1.25$) is about 7% for low heads

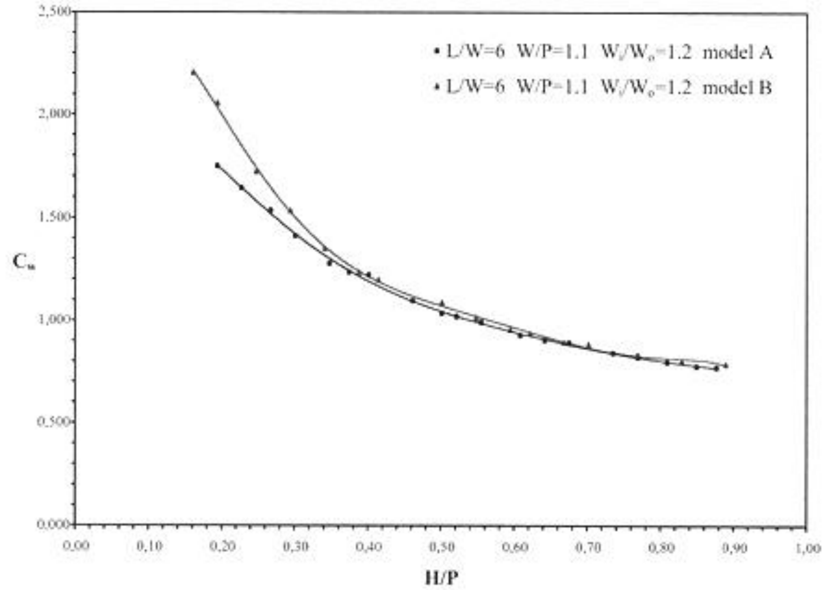

Figure 4. Comparison of flow coefficients of PKW model A and B.

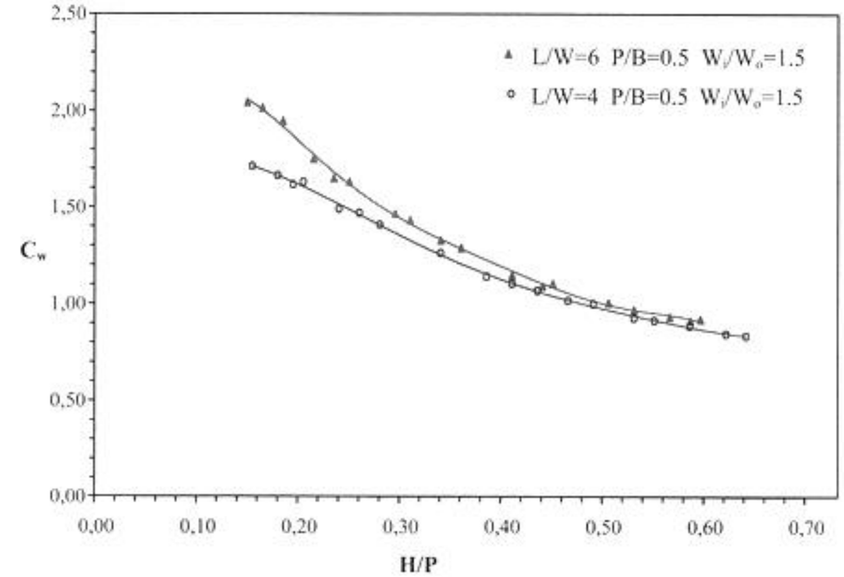

Figure 5. Flow coefficient depending on L/W ratio.

of $H/P = 0.25$ and 4% for medium heads of $H/P = 0.5$. The difference between the curves of model B07 ($W/P = 1.25$) and B09 ($W/P = 0.99$) is about 9% for low heads of $H/P = 0.25$ and 6% for $H/P = 0.5$.

4.4 *Influence of key widths W_i/W_o*

To achieve the hydraulically optimal ratio between the inlet key width W_i and the outlet key width W_o, three PKW models with the same ratio $L/W = 6$ were tested (Fig. 7). The comparison between the flow coefficients of the models of $W_i/W_o = 1.2$ and $W_i/W_o = 1.5$ shows that the lower W_i/W_o ratio increases the discharge capacity of 5% for low heads and of 3% for medium ones.

4.5 *Influence of PKW position*

The first test concerning the position of model A was performed with a downstream water level at the same level as PKW base. The second test was performed by raising the position of the PKW

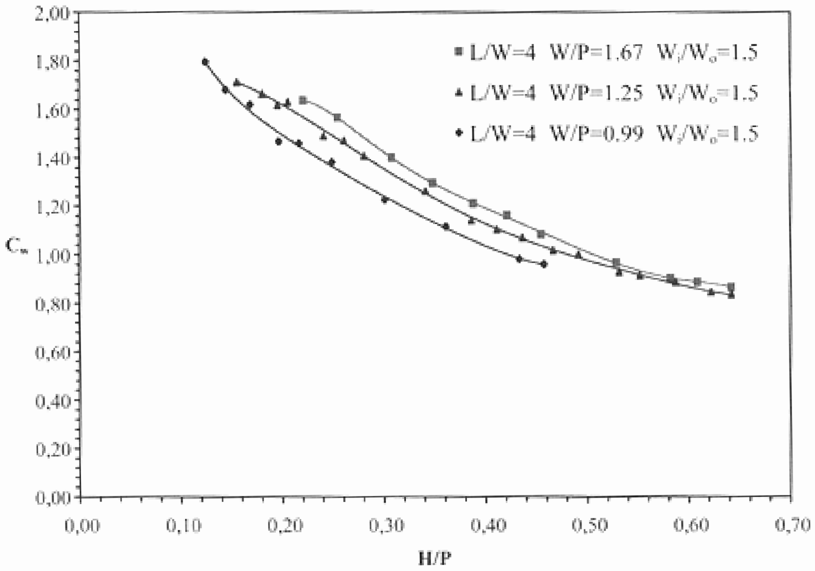

Figure 6. Flow coefficient depending on W/P ratio.

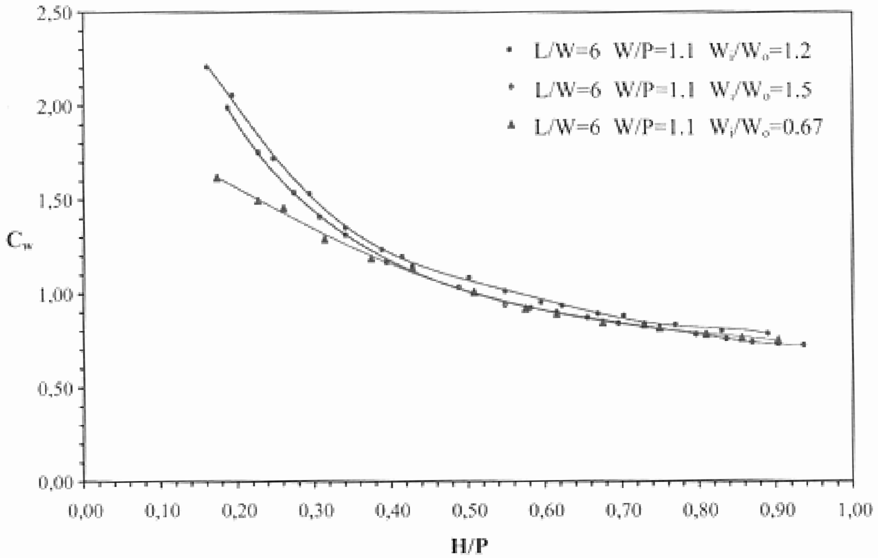

Figure 7. Flow coefficient depending on upstream and downstream key widths.

by 16 cm. Figure 8 shows flow coefficients of the two tested positions of PKW model A. The two curves are almost identical. The same performance for both locations was achieved.

4.6 *Influence of inlet key slope*

To determine the influence of the inclination of key bottom on the flow, two models were tested. The first one had horizontal inlet key slopes and inclined outlet keys. The second model was characterized by inclined inlet and outlet keys. Figure 9 shows that the model with strike angles increased the discharge capacity of the PKW by about 12% for $H/P > 0.6$ compared with the model with zero strike.

4.7 *Influence of the key length*

Side walls with door-to-short overhangs are more stable and easier to implement than door-to-long fakes. Two models of the same ratio $L/W = 6$ were tested to determine their hydraulic efficiency.

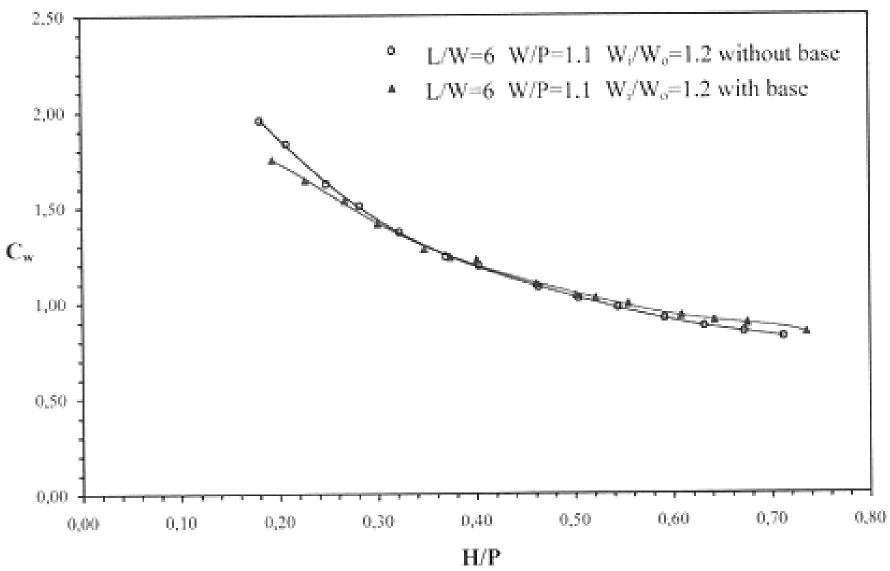

Figure 8. Flow coefficient based on PKW position.

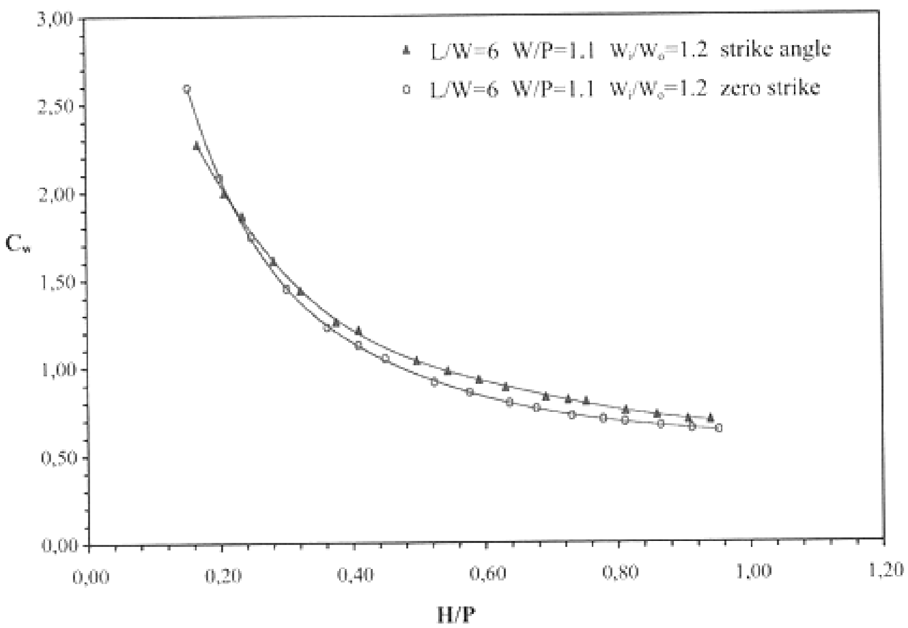

Figure 9. Flow coefficient based on the inlet key slope.

Figure 10 shows that increasing length of the sidewalls has no impact on the performance of the PKW as long as H/P is lower than 0.7. For important heads of $H/P > 0.7$, the model with B = 62.5 cm is by 3% more efficient than the model with B = 41 cm.

4.8 *Influence of the outlet key*

To check the impact of a ski jump at the downstream end of the oulet key on the performance of PKW, two tests were performed on a model with $L/W = 4$, $W/P = 1.25$ and $W_i/W_o = 1.5$. The first test was done without obstacle at the outlet key outlet (Fig. 11). For the second test a ski jump at the downstream end of the outlet key was implemented (Fig. 12). Figure 13 shows that the presence of an obstacle at the downstream end of the outlet key of the PKW reduces the performance of PKW significantly. The reduction is about 20% for $H/P < 0.5$.

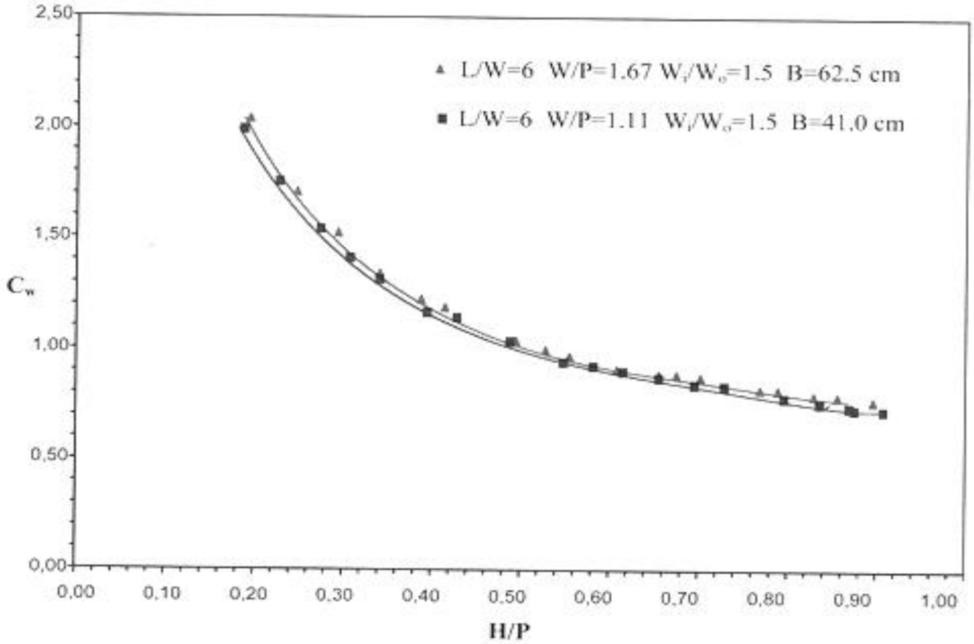

Figure 10. Flow coefficient based on the sidewall length.

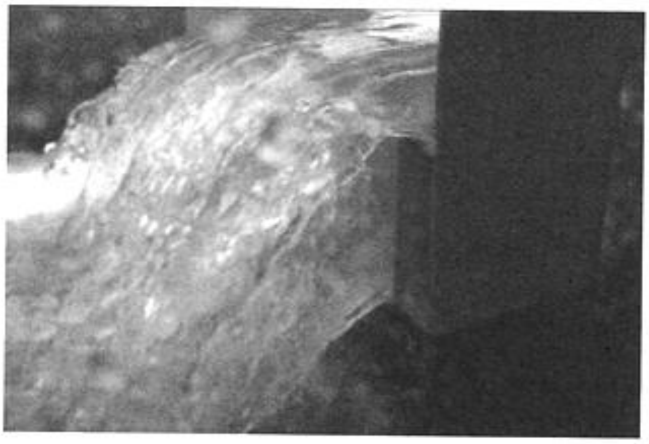

Figure 11. Flow on model without ski jump.

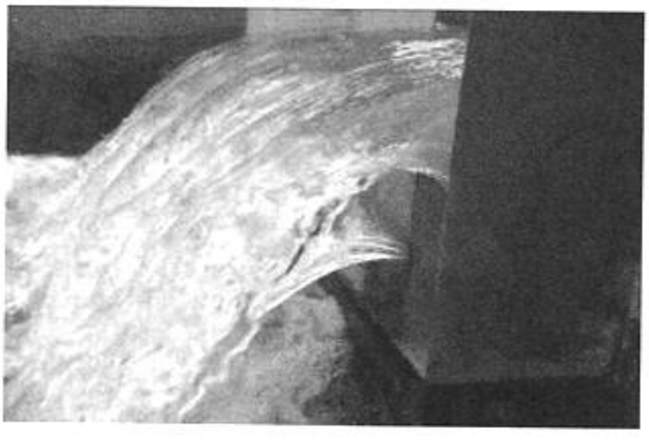

Figure 12. Flow on model with ski jump.

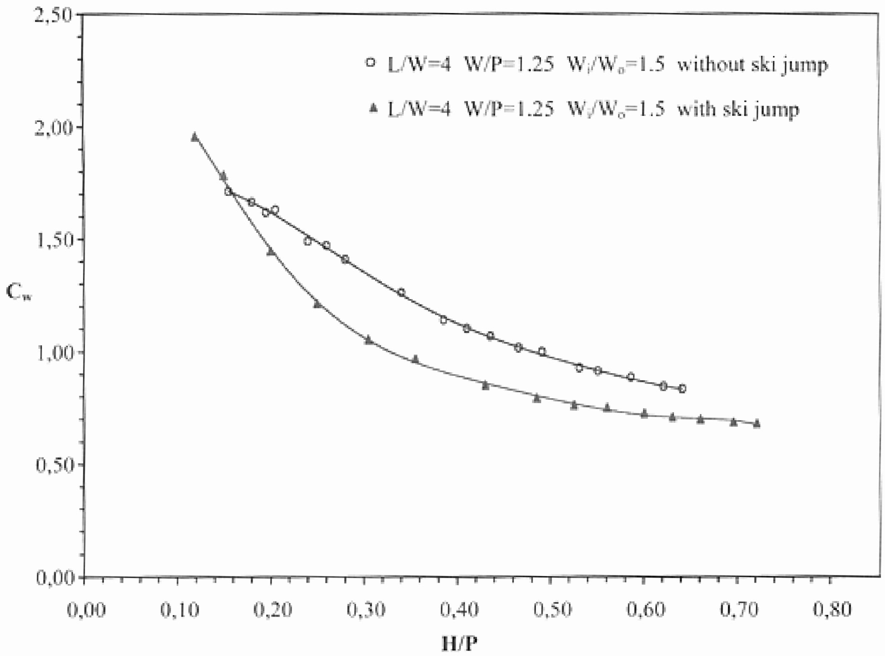

Figure 13. Flow coefficient influenced by a downstream ski jump.

5 CONCLUSION

This study showed that the flow coefficient is related to several dimensionless parameters:

$$C_W = f(H/P, L/W, W/P, W_i/W_o) \tag{9}$$

The results of the physical modeling tests with fourteen different PKW models reveal:

- The PKW is a more efficient solution than the classic Creager weir;
- The performance of PKW Type B is higher than Type A;
- The PKW has a higher performance when the H/P ratio is lower. Therefore a PKW should be operated for heads lower than half of the weir height P;
- For steep key slopes the effect of L/W is very apparent;
- By increasing the height of the weir, 25% higher performance can be achieved for low heads, for medium heads only 5%;
- PKW Type B allows a better performance if the width of the inlet key is 1.2 times the width of the outlet one. From a practical and economic point of view this fact is particularly interesting because the concrete volume is the same;
- The PKW is designed to be placed on gravity dams or in spillway channels of earth dams. Tests have shown that the same performance for both cases of location can be achieved;
- A ski jump at the downstream end of the outlet key allows avoiding the impact of the water jet on the dam body; however the performance of the PKW decreases.

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