Labyrinth and Piano Key Weirs – PKW 2011 – Erpicum et al. (eds)
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General comments on Labyrinths and Piano Key Weirs: The past and present

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ABSTRACT: Labyrinth weirs are the first sills based on the concept of an increase in developed crest length for a given weir width. This article begins with a comparison between data of existing weirs. After these considerations, the studies performed by Hydrocoop and Biskra University on Piano Ney Weirs are presented. Data concerning PKW under construction are then given, and the article ends with a proposition of reference designs for PKW.

1 INTRODUCTION

Hydrocoop is a non profit making Association promoting international technical cooperation in dam engineering with special focus on flood control, spillways and sedimentation. It has accordingly, over the past ten years, studied two innovative devices for existing or new free-flow spillways: Piano Keys Weirs and low cost Concrete Fuse Plugs. Hydrocoop has promoted and coordinated relevant hydraulic model tests in five countries: France, Algeria, India, China, Vietnam.

Since ten years the University of Biskra (Algeria) has been deeply associated with Hydrocoop as well for theoretical studies as for hydraulic model tests (Mr Ouamane). The University has built a specific hydraulic flume mainly devoted to the studies of PKW.

2 EXISTING LABYRINTH WEIRS AND ASSIMILATED

2.1 *Typical design*

Most existing traditional labyrinths have similar data: vertical walls on a horizontal bottom slab with trapezoidal or triangular layout with same shape upstream and downstream. The most usual properties are gathered in the following table.

These designs require approx. 5 to 10 m^3 of reinforced concrete per m^2 of nape saved.

Table 1. Typical designs.

Properties	Unit	Value
Developed length/Spillway width	–	3 to 5
Wall height P	m	2 to 4
Nape depth	m	1.5 to 2 ($0.5 \times P$)
Depth saving (vs Creager weir)	m	~1 ($0.3 \times P$)
Specific discharge capacity at design head	m^3/s/m	~10
Specific discharge capacity increase (vs Creager weir)	m^3/s/m	~5

Table 2. Ute labyrinth weir main properties.

Properties	Unit	Value
Wall height P	m	9
Weir width W	m	250
Specific discharge capacity at design head	$m^3/s/m$	60
Depth saving (vs Creager weir)	m	3.5
Area of walls and basis as compared with depth saving	m^3/m^2	>15

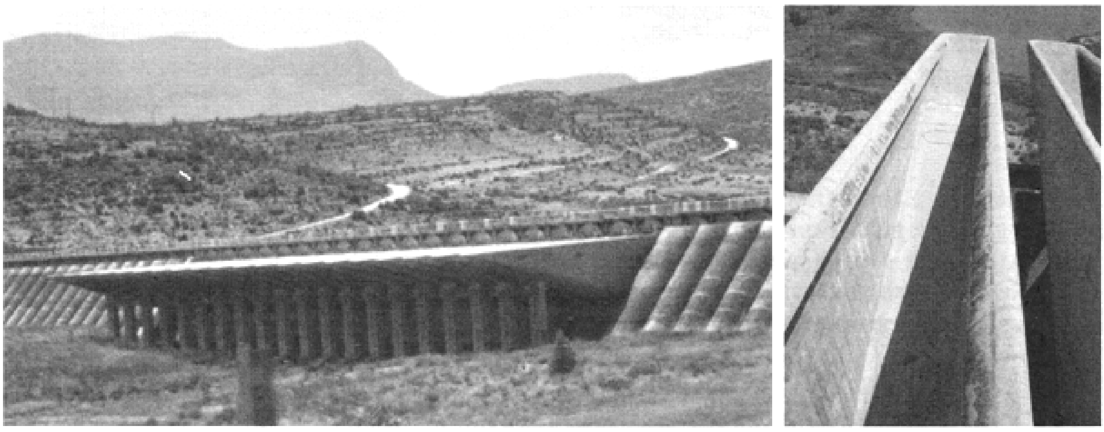

Figure 1. Beni Bahdel labyrinth spillway upstream view (left) and top view (right).

2.2 *Very large labyrinth weirs: the example of Ute (U.S.)*

Three very large labyrinth weirs have been constructed. The best example is the spillway built at Ute Dam, U.S.

15 000 m^3 of concrete and 3 000 t of reinforcing steel have been used for the construction of Ute labyrinth weir. The nape depth saving is about 900 m^2, hence over 15 m^3 of reinforced concrete are required per m^2 of depth saving.

2.3 *Drawbacks of traditional labyrinth spillways*

The main advantage of labyrinth weirs is the easy construction of vertical walls. However, there are three main drawbacks. First, the reinforced concrete quantities are high. Then, the hydraulic efficiency is much reduced for high discharge. Moreover, labyrinth weir implementation requires a massive basis which prevents their construction upon usual spillways footprint. Most existing labyrinth weirs have been placed on a flat bank of the river.

2.4 *Special labyrinths with inclined walls*

The Beni Bahdel labyrinth weir has been constructed in 1938 in Algeria, and was designed with upstream overhangs (Fig. 1). Beni Badhel dam is a multiple arch 55 m high dam. The spillway, which can be assimilated to a labyrinth weir, has a rectangular layout with very long upstream overhangs, developing a crest length 15 times higher than the weir width. Its discharge capacity is about 1 200 m^3/s, hence approx. 10 $m^3/s/m$ with an upstream head of 0.5 m, instead of 2.8 m for a Creager weir. However, the area of wall per m^2 of nape depth saved is more than 30 m^2. This spillway is rather similar with a PKW having only upstream overhangs.

The Bakhada dam, a 45 m high rockfill dam, has been built in 1936 in Algeria and raised with labyrinth in 1960. The spillway discharge has a 2 000 m^3/s discharge capacity and can be assimilated to a labyrinth weir. Its specific discharge capacity is about 15 $m^3/s/m$, and its shape appears more cost-effective than Beni Badhel spillway. The layout is rather similar to a PKW having only upstream overhangs, with a trapezoidal shape on a curved basis (Fig. 2).

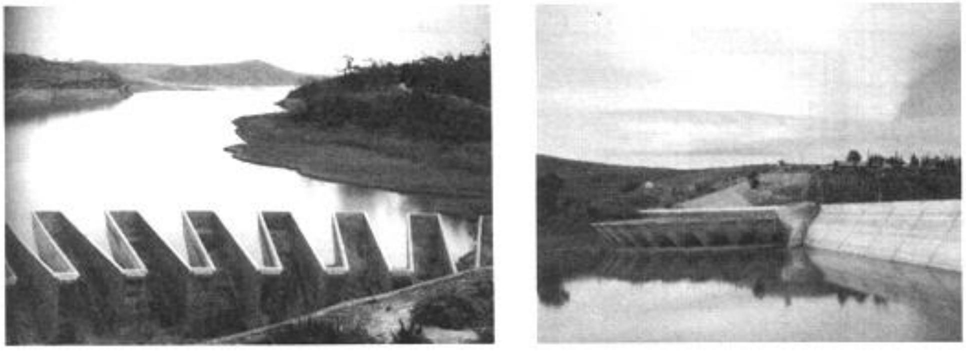

Figure 2. Bakhada labyrinth spillway dowstream view (left) and upstream view (right).

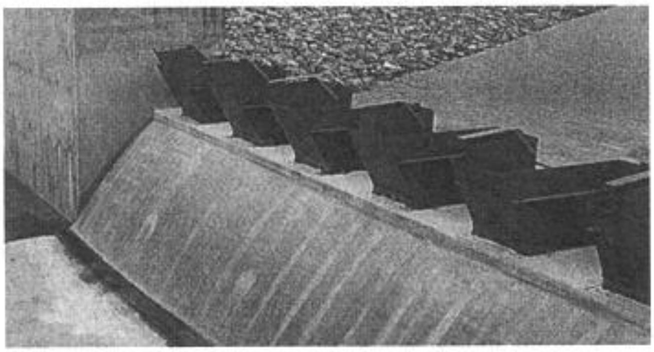

Figure 3. Hydroplus fusegates.

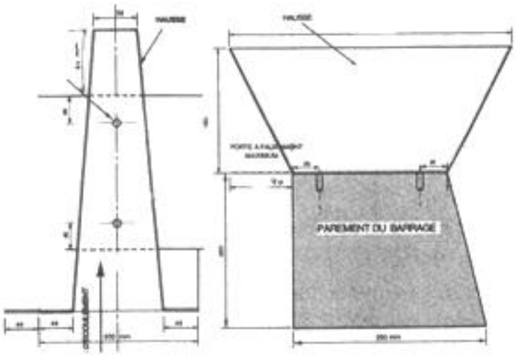

Figure 4. First design – trapezoidal shape with overhangs.

2.5 *Fuse gates (Hydroplus)*

Since 1991, Hydroplus has built labyrinth fusegates for about 40 dams with labyrinth height between 1 and 7 m. They are made of steel or reinforced concrete. For tilting purpose, the shape usually includes a single downstream overhang. The developed length is usually close to 3 times the spillway width with a trapezoidal layout. Such fusegates may be placed upon existing spillways. Tilting has already happened for 10 dams, each time in accordance with design level.

3 STUDIES OF PINAO KEY WEIRS (PKW) SINCE 1998 BY HYDROCOOP AND BISKRA UNIVERSITY

3.1 *A brief historic*

The first model tests were performed for Hydrocoop in 1998 at the LNH in Chatou (France). As shown on the scheme here below, the final rectangular shape was not yet adopted, but the main principle of overhangs was included.

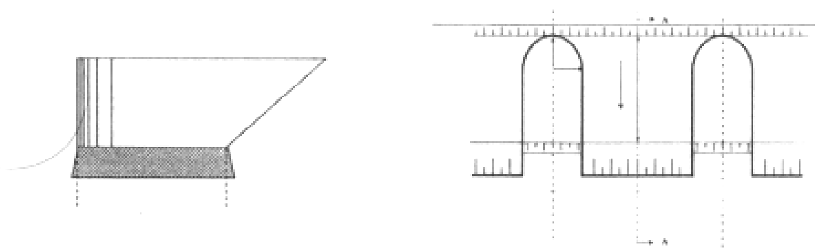

Figure 5. Later design – rectangular shape with overhangs.

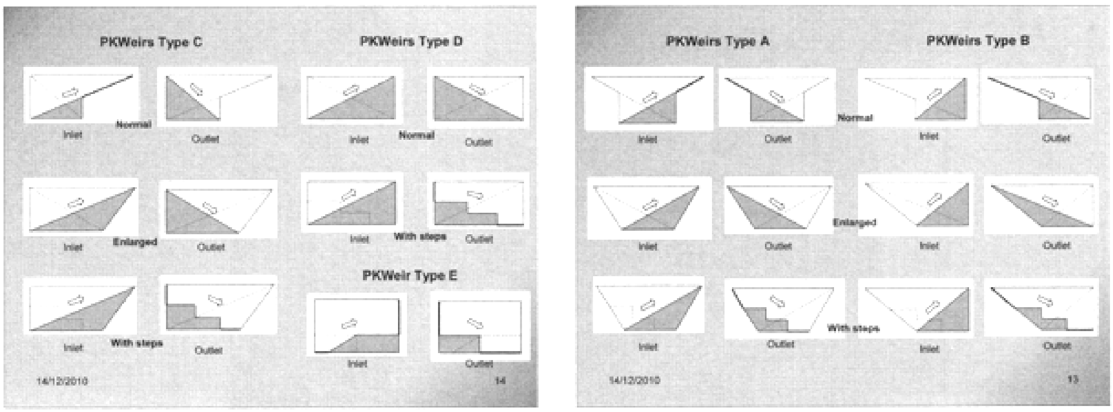

Figure 6. Catalogue of the configurations tested.

Improvements were then suggested by P. Blanc and F. Lempérière in Hydropower and Dams (2001 – Issue 4) for traditional labyrinths and for associating a rectangular layout with overhang. Tests in Biskra University (Algeria) were performed in 2002 on the here below model. Many tests have followed in 2002 and 2003, in Biskra, Chatou and Roorke (India) leading to a basic paper on PKW by F. Lempérière and A. Ouamane (Hydropower & Dams – Issue Five, 2003).

Since 2003, hundreds of tests were promoted by Hydrocoop and performed in Marolles (Hydroplus, France), in India (Roorkee University), in China (IWHR Laboratory in Beijing) and in Vietnam (Ho Chi Minh University). Many model tests for theoretical studies and researches on various types of PKW have been performed at Biskra.

All these studies and tests have the same goals. On the one hand, they aim in finding a compromise between the hydraulic efficiency, the structural and relevant construction problems, and the economical considerations. On the other hand, they aim in elaborating some standard models of PKW to facilitate preliminary designs, cost estimation and comparison with other solutions.

Many models have been tested including various widths and fillings of the inlet or outlet keys, various noses shapes, study of the consequences of floating debris, etc. The following plots show the existing "catalogue" of various configurations envisaged and tested.

3.2 *Main results*

It seems that PKW Type B (only upstream overhang) appears as the most hydraulic efficient solution, with probably same width for inlet and outlet keys. However, floating debris may require special care. This solution is maybe the best solution for new dams.

The PKW Type A (upstream and downstream overhangs) has a good hydraulic efficiency, with inlet keys larger than outlet keys (ratio about 1.2). This is maybe the best solution for most existing dams.

The PKW Type C (only downstream overhang) doest not appear more interesting except for fusegates or for huge floating debris management.

PKW Type D and E (without overhang) are improved classic labyrinths. They may be a solution when there is space enough in banks, in river or if there is lack of skilled workers.

Table 3. Bambakari dam PKW main properties.

Properties	Unit	Value
Wall height P	m	3.2
Height P_m	m	2.13
Weir width W	m	200
PKW longitudinal length	m	8.52
Outlet key width	m	1.55
Inlet key width	m	1.2
Developed length ratio	–	6
Number of PKW units	–	58
Specific discharge capacity at design head	$m^3/s/m$	5

In each case, the following conclusions of PKW shapes have been shown.

Profiling the nose under the outlet key is efficient.

Developed length ratio L/W around 4 or 5 seems a reasonable compromise. Ratio of 6 or 7 may be used in special cases.

Filling the outlet keys with steps (to combine PKW with a stepped spillway) does not reduce much the discharge capacity providing that the height of the steps remains under certain limitation.

The hydraulic efficiency remains good even when the PKW is submerged with a high downstream level.

The best dimensions for an optimal design vary with the discharge. For instance, the optimal ratio between the widths of the keys (W_i/W_o) is not the same for a small or a high discharge through the PKW.

The trapezoidal layout is not necessary when associated with inclined walls because the adjustment of the wet section to the flow is made by the walls slope (PKW). The trapezoidal layout appears logical hydraulically when associated with vertical walls and flat bottom. It keeps a same speed along the inlet. However even in this case the rectangular lay out may be more cost efficient than the trapezoidal layout because the average width of the inlet and outlet may be reduced as well as the length (and the area and cost) of the structure. PKW model D and E are thus proposed with vertical walls and rectangular layout.

4 CURRENT PKW PROJECTS

4.1 *Overview*

EDF, which was the first Owner to build PKW, presents in separate papers its projects and its improvements on various points of the design and construction methods for PKW already built or under design.

Hydrocoop was asked for giving advices for various PKW projects. Among those, the following ones are under construction: Bambakari dam in Burkina Faso, Lhasi dam in India, Van Phong dam in Vietnam and Dakmi 2 dam in Vietnam.

The first two are presented here while the last ones are presented by M. Ho Ta Khanh in separate papers as well as other projects under study in Vietnam.

4.2 *Bambakari dam (Burkina Faso)*

The PKW spillway of Bambakari dam is designed in order to spill 1 000 m^3/s for a design upstream head of 0.86 m. The preliminary design was presented in March 2009 at Liège PKW workshop. The final design (PKW type A) is now under completion. Its main properties are gathered in the following table.

This cross section has been selected to be used as a test for first construction of a PKW type A "normal" in Burkina Faso. Because of the local conditions (PKW set on the ground) another solution such as type A "enlarged" or type E would have been probably also convenient.

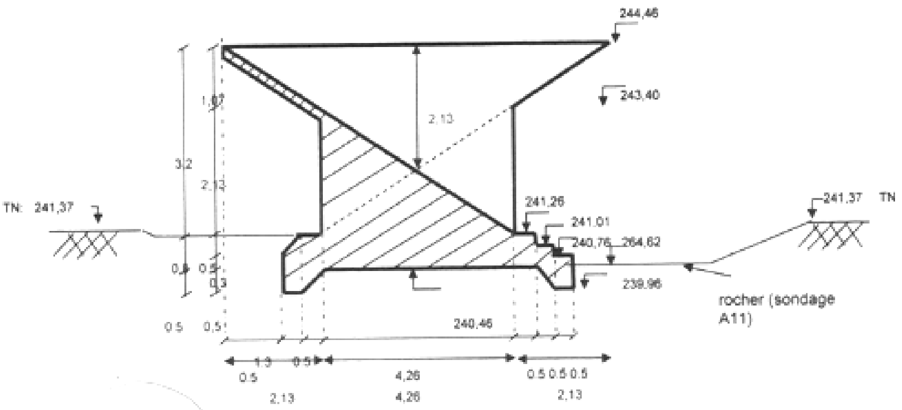

Figure 7. Bambakari dam PKW – cross section.

Table 4. Lhasi dam PKW main properties.

Properties	Unit	Value
Wall height P	m	6.5
Height P_m	m	4
Weir width W	m	115
PKW longitudinal length	m	16
Outlet key width	m	2.4
Inlet key width	m	3
Developed length ratio	–	6
Number of PKW units	–	18
Specific discharge capacity at design head	$m^3/s/m$	9.7

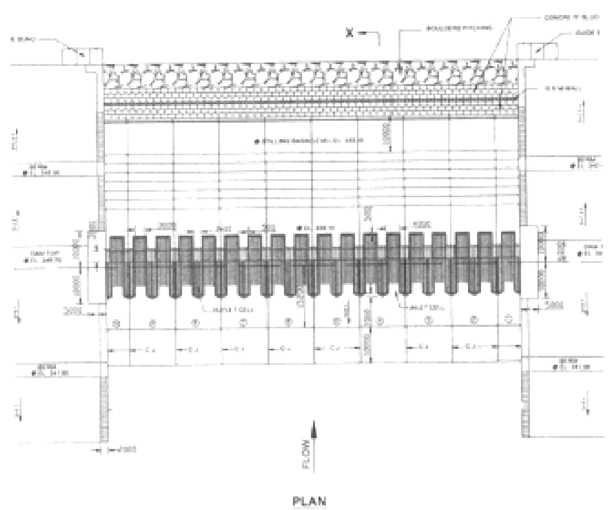

Figure 8. Lhasi dam PKW – plan view.

4.3 *Lhasi dam (India)*

The PKW spillway of Lhasi dam is designed in order to spill 1 115 m^3/s for a design upstream head of 0.86 m. Following Hydrocoop advices, the preliminary PKW design presented in October 2009 at Lyon PKW workshop, was slightly changed. The total length of the weir W has been reduced from 128 to 115 m, the number of elements N_u from 20 to 18, and a PKW type A "enlarged" was preferred to a "normal" one.

Plan view and cross section as presently proposed by the local designer as per the following drawings (Fig. 8 and 9).

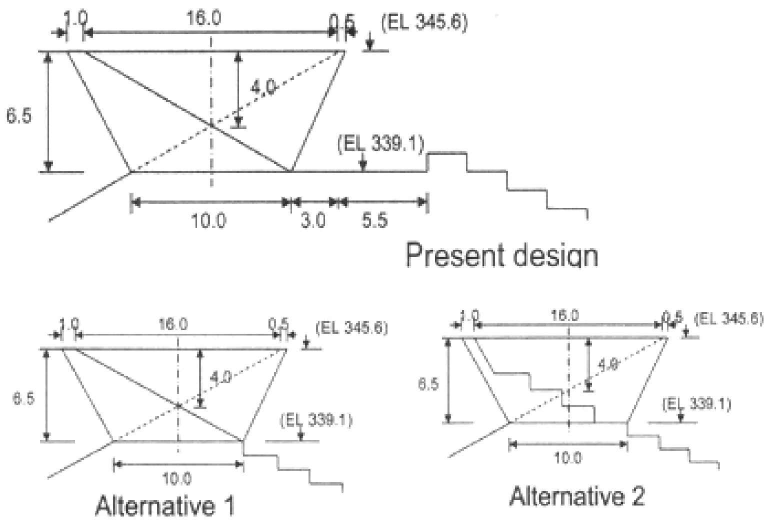

Figure 9. Lhasi dam PKW – cross sections.

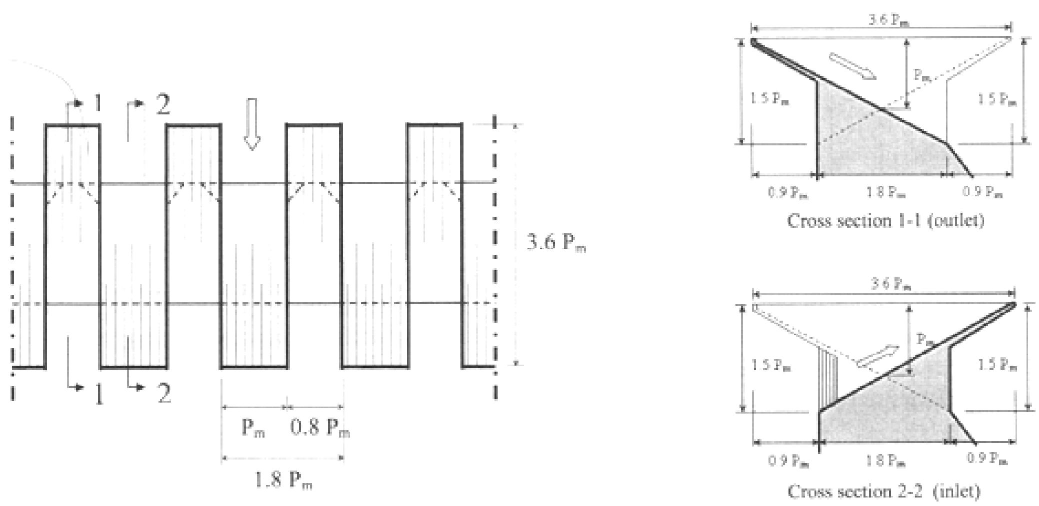

Figure 10. Proposed reference design pour PKW model A – plan view (left) and cross sections (right).

5 CONCLUSION – REFERENCE DESIGNS

5.1 *Reference designs*

PKW are cost efficient but it is not easy to optimize the shape for each scheme. It appeared useful, using results of many hydraulic model tests, to propose some reference designs and relevant hydraulic performances in order to help owners and consultants, either for using directly these models, or for using them for preliminary designs to be optimized by specific tests.

The principle of these models is to have the best ratio of cost per saving in nape depth or per specific flow increase. They may not represent the maximum saving.

They are possibly not the optimum shape but are probably most often rather close to it. They may be easily tested in existing laboratories.

Hereafter are presented the reference configurations for PKW model A (upstream and downstream overhangs), model B (only upstream overhangs) and model E (without overhangs). PKW model C (one downstream overhang) is not presented here but should be studied.

PKW model A and B are presented in Appendix to ICOLD Bulletin 144: Cost Savings in Dams.

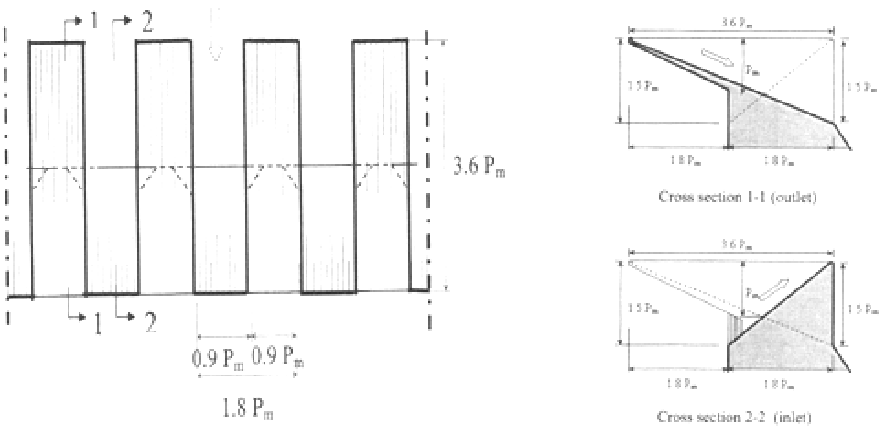

Figure 11. Proposed reference design pour PKW model B – plan view (left) and cross sections (right).

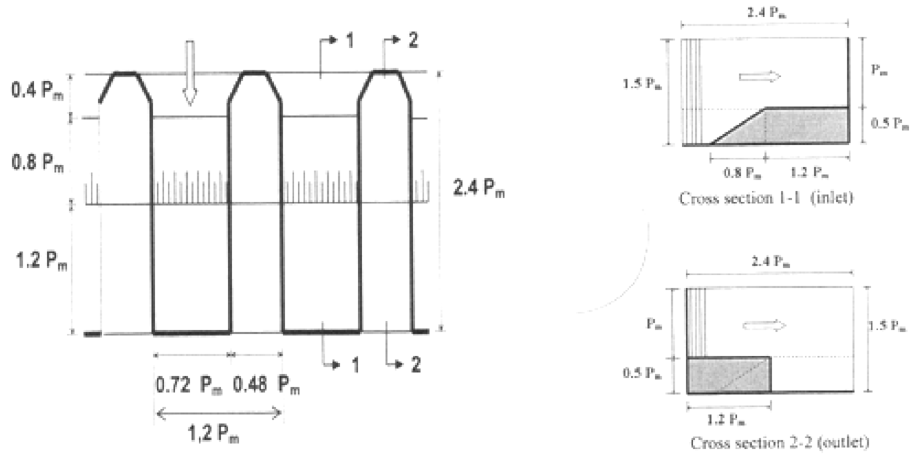

Figure 12. Proposed reference design pour PKW model E – plan view (left) and cross sections (right).

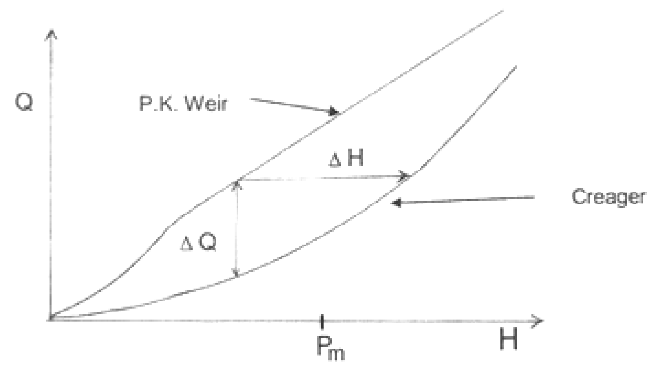

Figure 13. Hydraulic performance of reference designs.

5.2 *Hydraulic performance of reference designs*

The hydraulic performance is measured by comparison with a Creager Weir. The key economic parameters are the saving ΔH in nape depth H or the increase ΔQ in specific flow Q as compared with a Creager Weir ($Q\ (m^2/s/m) = 2{,}15\ H^{1,5}$ (H in m)).

For reference designs A and B, the saving ΔH in depth is close to $0{,}5 \times P_m$ (maximum wall height of the PKW) for usual nape depths (H between 0,4 P_m and 1,5 m). The discharge increase ΔQ is close to the discharge of a Creager weir overtopped by a nape depth equal to P_m. The volume of reinforced concrete is about half the volume of traditional labyrinths for a same saving.