# Method for the preliminary design of Piano Key Weirs – Méthode de pré-dimensionnement pour les déversoirs en touches de piano

O. Machiels[1, 2], S. Erpicum[1], P. Archambeau[1], B. J. Dewals[1] and M. Pirotton[1]

[1]HACH unit, Department ArGEnCo, University of Liege, Chemin des chevreuils, 1 – B52/3, B-4000 Liege, Belgium ; TEL (+32) 4 366 95 60; FAX (+32) 4 366 95 58; email: omachiels@ulg.ac.be

[2]Fund for education to Industrial and Agricultural Research

**Abstract**

The Piano Key Weir (PKW) is a particular geometry of weir associating to a labyrinth shape the use of overhangs to reduce the basis length. The PKW could thus be directly placed on a dam crest. Together with its important discharge capacity for low heads, this geometric feature makes the PKW an interesting solution for dam rehabilitation. However, its hydraulic design remains problematic, even at a preliminary stage.

This paper presents a preliminary design method based on results of experimental tests. The method enables to design project models by extrapolation of characteristics of existing idealized scale models.

A practical application is presented to illustrate the method.

*Le déversoir en touches de piano (PKW) est une forme particulière de déversoir en labyrinthe associée à l'utilisation de porte-à-faux, permettant de réduire son emprise en base. Le PKW peut ainsi être placé directement en crête de barrage. Cette particularité* *géométrique, combinée à une importante capacité de débitance, fait du PKW une solution efficace pour la réhabilitation d'ouvrages de rétention existants ou pour l'optimisation de projets neufs. Cependant, le dimensionnement hydraulique d'un PKW reste problématique, dès les premières étapes de sa conception.*

*Cet article présente une méthode de pré-dimensionnement basée sur l'exploitation de résultats expérimentaux. Le dimensionnement de modèles de projet est ainsi réalisé par extrapolation des caractéristiques géométriques et hydrauliques de modèles réduits idéalisés. Une application pratique est également exposée afin d'illustrer la méthode.*

**Key Words :** Piano Key Weirs, Design method

## 1. INTRODUCTION

Piano key weir is an original type of weir developed by Lempérière (Blanc and Lempérière 2001, Ouamane and Lempérière 2003) to combine the interest of a labyrinth weir with overhangs to facilitate the weir location on the dam crests (Figure 1). The first scale model studies showed that this new type of weir can be four times more efficient than a traditional Creager at constant head and crest length on the dam (Ouamane and Lempérière 2006a).

The PKW shows geometric specificities such as up- and/or downstream overhangs with variable width, inlet and outlet bottom slopes, which involve a large set of variable parameters (Figure 1). The "PKW-unit" is the smallest extent of a complete PKW composed of an entire inlet key with two side walls and half an outlet key on both sides. The main geometric parameters of a PKW are the weir height $P$, the number of PKW-units $N_u$, the lateral crest length $B$, the inlet and outlet widths $W_i$ and $W_o$, the up- and downstream overhang lengths $B_o$ and $B_i$ and the wall thickness $T$.

Experimental studies have been and are currently carried out in different laboratories to improve the understanding of the flow behavior over PKW (Anderson and Tullis 2011, Machiels et al. 2011, Machiels 2012), and to characterize the influence of a number of geometrical parameters on the discharge capacity of the PKW (Hien et al. 2006, Ouamane and Lempérière 2006b, Le Doucen et al. 2009, Machiels et al. 2010, Machiels 2012).

Based on the first experimental results, numerical models have been developed. A 3D model is used by EDF to design the prototype models which will be tested in laboratories (Luck et al. 2009, Pralong et al. 2011). A 1D model has been developed at the University of Liege to improve the design of the experimental models used for parametric studies (Erpicum et al. 2010, Erpicum et al. 2011).

The first real size PKWs have been built by EDF in the last six years (Laugier 2007, Bieri et al. 2009, Laugier et al. 2009, Vermeulen et al. 2011, Laugier et al. 2012). Till now, the hydraulic design of a PKW is mainly performed on the basis of experimental knowledge and numerical models, used to design an initial geometry, which is then studied on scale models and modified step by step following the ideas of the project engineers (Ribeiro et al. 2007, Erpicum et al. 2012).

By exploitation of existing experimental results, a preliminary design method for PKW has been developed and is presented in this paper. To limit the experimental studies, the design method aims at approaching as well as possible the final project model, compromise between hydraulic optima, respect of project constraints and cost effective building. To illustrate the method developed in this paper, it is applied to a PKW project on a large dam.

## 2. DESIGN METHOD

The design method is based on the project constraints (discharge, reservoir levels, available space …) and on extrapolation of existing experimental results from a reference scale model. By the study of the different possibilities to scale the reference models, the final design is defined depending on project engineer's interests (increase of the security level, increase of the reservoir capacity, decrease of the structure dimensions …).

The elements necessary to the design method are categorized in project elements and reference model elements. The project elements are the hydraulic and geometric specificities of the project (discharge, maximal head and available width). Regarding the reference model, a release capacity curve, issued from experimental tests, is necessary as well as geometric characteristics of the tested model.

Based on the project elements, different efficient designs may exist. The first step of the method aims at defining these different possibilities as a function of the number of PKW-units in the structure, by scaling of the geometric and hydraulic parameters of the reference model.

The PKW-unit width $W_u$ is defined as a function of the number of PKW-units $N_u$ and the available width for the project $W$:

$$W_u = \frac{W}{N_u} \qquad (1)$$

The scale of the project model $x$ is then defined as the ratio between the widths of PKW-units on the project $W_u$ and on the reference model $W_u$*.

$$x = \frac{W_u}{W_u^*} \qquad (2)$$

Applying this scale on the design water head $H$, the corresponding head on the reference model $H^*$ is:

$$H^* = \frac{H}{x} \qquad (3)$$

The discharge coefficient $C_{dw}$, of the Poleni equation (Eqn (4)), usually used to characterize weirs efficiency, is a non-dimensional number. There is thus no scaling on its value and the $C_{dw}$ value of the project model for the design head $H$ is equal to the $C_{dw}^*$ value of the reference model at the corresponding head $H^*$ (Eqn (5)).

$$Q = C_{dw}.W.\sqrt{2gH^3} \qquad (4)$$

$$C_{dw}(H) = C_{dw}^*(H^*) \qquad (5)$$

Inserting Eqn (1) to (3) and (5) in the Poleni equation (4), a relation between the head and the discharge is obtained for the project model depending on the hydraulic and geometric characteristics of the reference model ($W_u^*$ and $C_{dw}^*$), the project constraint ($W$) and the number of PKW-units on the project.

$$Q = C_{dw}^*.W.\sqrt{2gH^3} \quad \text{with } C_{dw}^* = f\left(\frac{H.W_u^*.N_u}{W}\right) \qquad (6)$$

If the discharge coefficient of the reference model is not known for the corresponding head, its value is calculated by extrapolation in-between the existing values. The accuracy of the design method is thus directly link to the experimental tests accuracy and to the number of available results for the reference model.

By drawing the head/discharge curves defined by Eqn (6) for different numbers of PKW-units and limiting these curves to head and discharge values under the design head and over the design discharge, different designs may respond to the project constraints.

The second step of the method is then to optimize remaining parameters depending on the project engineer's interests, to clearly define the final design. By application of the scale factor to the reference model dimensions $X^*$, the project model dimensions $X$ are completely defined (Eqn (7)), permitting the optimization of the final design including structural, economical or hydraulic criteria.

$$X = x.X^* \tag{7}$$

The method can finally be summarized as the following four steps:

1) Choose of a reference model;
2) Scaling of the geometric and hydraulic characteristics of the reference model, corresponding with different number of PKW-units;
3) Isolation of the designs enabled to respond to the project constraints;
4) Optimization of the design based on structural, economical nor hydraulic criteria, depending on the project engineer's interests.

This method has been applied to the pre-design of varied PKW configurations (Machiels 2012) highlighting a good prediction of the experimental results as long as the side effects are still moderated. This is true for a large number of PKW-units or for still reservoir conditions.

## 3. APPLICATION

To show the interest of the method to optimize the design regarding the project engineer's interests, it has been applied to the preliminary design of a PKW.

Let us consider a dam project with features as summarized in Table 1. The discharge to release on the PKW at maximal reservoir level is 400 m³/s. The specific discharge is thus 11.5 m³/s/m, to be evacuated under a head of 2 m.

The choice of the reference model highly influences the accuracy of the final design and has to be realized according to the project constraints and the range of available results (Machiels 2012). From the different  available results from the literature (Hien et al. 2006, Le Doucen et al. 2009, Machiels et al. 2009), the model from Biskra (Ouamane and Lempérière 2006a) has been choosen as the reference model. Indeed, this model presents efficient geometric (symmetric overhangs of limited length) and hydraulic (adimensional head/discharge curve) characteristics regarding the project constraints. Furthermore, a large set of results are available for this geometry, which increases the method accuracy (Table 2). The geometric characteristics of the model are given in Table 3 and the experimental results are summarized in Figure 2 in terms of discharge coefficient $C_{dw}$ of the Poleni equation function of the ratio between the water head $H$ and the weir height $P$.

Considering a 5-units PKW, the width of each unit is 7 m (Eqn (1)). It represents a scale ratio of 42.4 between the project and the reference model (Eqn (2)). The corresponding design head on the reference model is 0.0471 m (Eqn (3)). By interpolation in-between the experimental results, the discharge coefficient of the PKW for the design head is equal to 1.56 (Eqn (5)). A PKW with 5 units placed on the crest of the projected dam enables to discharge 685 $m^3/s$ (Eqn (6)). A 5-units PKW enables thus to respect the project constraints.

The project characteristics calculated for $N_u$ varying from 5 to 11 are presented in Table 4. Figure 3 shows the head/discharge curves calculated for these $N_u$ values. Many solutions exist to ensure the dam safety. An optimization of the design on different parameters is thus possible.

An increase in the normal reservoir level enables to increase the hydropower capacity. A first optimization could thus consist in the limitation of the design head to 1.5 m, enabling to fix the normal reservoir level to 452.5 m NGF and limiting the solutions to $N_u$ values under 8 (Figure 3).

Another optimization could concern the structural constraints. By limitation of the basis position of the PKW over 446.5 m NGF (50 cm over the gated weir crest), the reservoir and the existing weir stays partially usable during PKW construction. There is thus no need of diversion works and the hydroelectric power plant could still been used during the PKW construction. The weir height is thus limiting under 6 m, what involve $N_u$ values over 6 (Table 4).

The final choice between the four last solutions could be realized to minimize the necessary volume of concrete. Considering a thickness of the walls of 20 cm (Table 4), the PKW design considering 7 units is the best solution.

Other designs may be optimum considering other criteria for optimization. For instance, a 5-units PKW ensures a higher level of security, and a 10-units PKW may suggest the use of prefabricated elements due to the smaller size of the alveoli.

## 4. CONCLUSION

Based on existing experimental results, a preliminary design method for PKW is proposed. In a first step, the different existing designs, enable to fit to the project constraints, are define by scaling the different geometric and hydraulic parameters of a reference model, considering different number of PKW-units. An optimal design is then clearly defined based on structural, economical or hydraulic criteria, depending on the project engineer’s interests. The application of the method highlights its interests to overcome varied projects constraints.

The accuracy of the method is mainly related to the available results accuracy. The insertion in this method of new experimental results from more efficient scale models would enable to improve the design efficiency. In the future, numerical models should help in improving this preliminary design, before detailed scale model studies.

# FIGURES

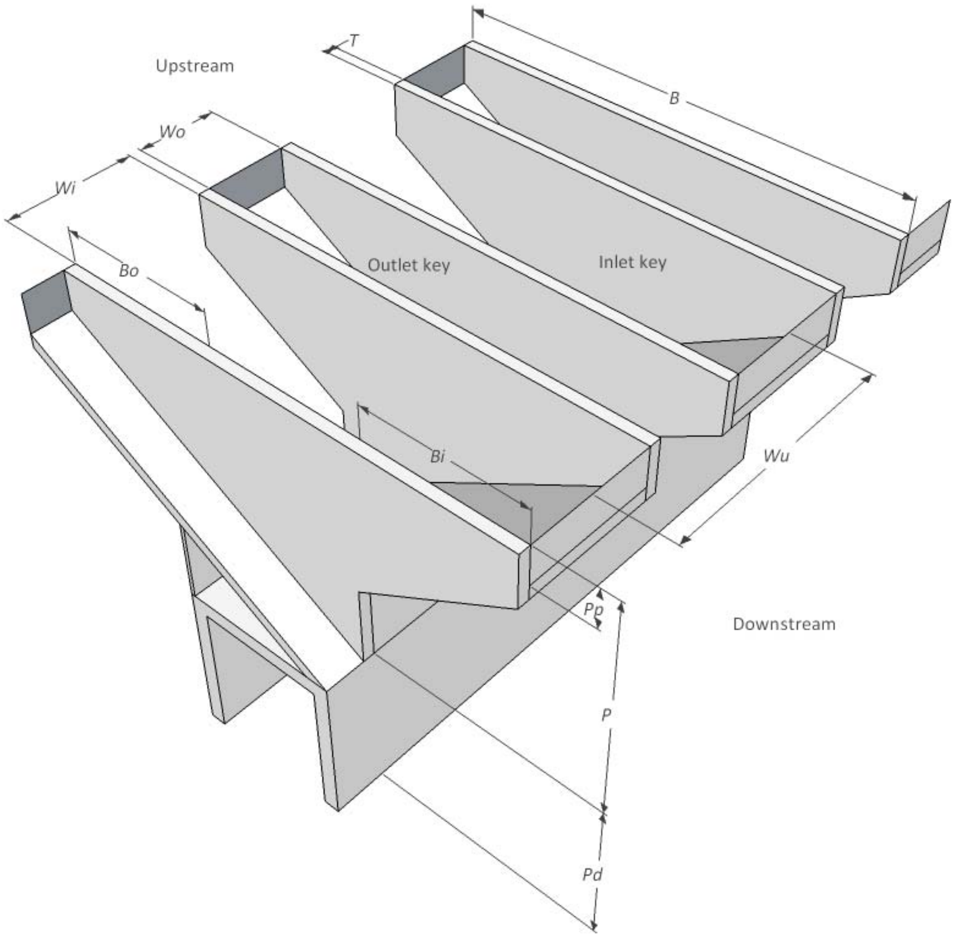


**Figure 1. 3D sketch of a PKW and main geometric parameters**

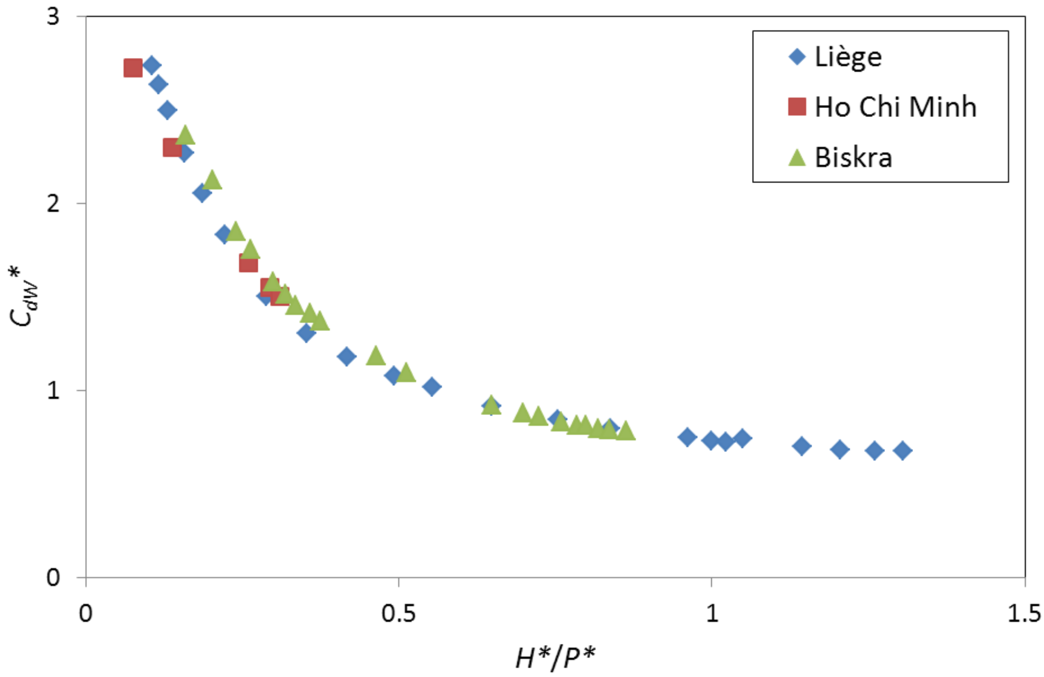


**Figure 2. Non-dimensional head/discharge curves for the available reference models**

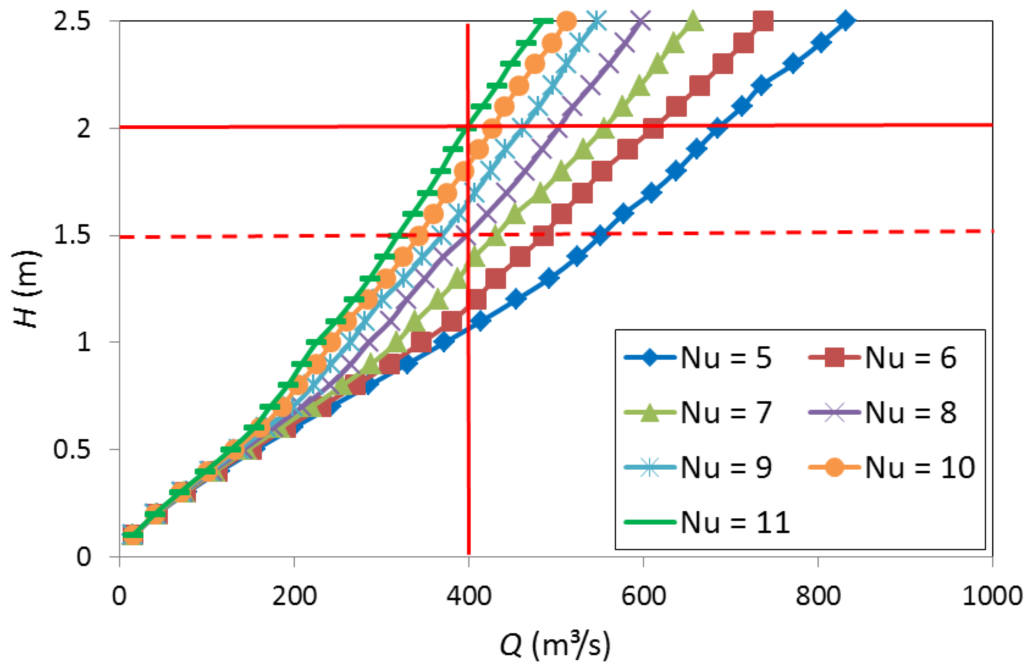


**Figure 3. Project head/discharge curves for various $N_u$ values**

# TABLES

**Table 1. Project dam and reservoir characteristics**

| | |
|---|---|
| **Available crest length** | 35 m |
| **Normal reservoir level** | 452.0 m NGF |
| **Maximal reservoir level** | 454.0 m NGF |

**Table 2. Hydraulic characteristics of the reference model (Biskra)**

| $H^*/P^*$ | $C_{dW}$ | $H^*/P^*$ | $C_{dW}$ |
|---|---|---|---|
| 0.16 | 2.36 | 0.51 | 1.10 |
| 0.20 | 2.12 | 0.65 | 0.92 |
| 0.24 | 1.85 | 0.70 | 0.88 |
| 0.26 | 1.76 | 0.72 | 0.86 |
| 0.30 | 1.58 | 0.76 | 0.84 |
| 0.32 | 1.52 | 0.78 | 0.82 |
| 0.33 | 1.45 | 0.80 | 0.81 |
| 0.36 | 1.42 | 0.82 | 0.80 |
| 0.37 | 1.37 | 0.84 | 0.79 |
| 0.46 | 1.19 | 0.86 | 0.78 |

**Table 3. Geometric characteristics of the reference model (Biskra)**

| | |
|---|---|
| **$P^*$ (m)** | 0.155 |
| **$W_i^*$ (m)** | 0.089 |
| **$W_o^*$ (m)** | 0.074 |
| **$B_o^*$ (m)** | 0.103 |
| **$B_i^*$ (m)** | 0.103 |
| **$T^*$ (m)** | 0.003 |
| **$B^*$ (m)** | 0.412 |

**Table 4. Project characteristics for various $N_u$ values**

| $N_u$ | *5* | *6* | *7* | *8* | *9* | *10* | *11* |
|---|---|---|---|---|---|---|---|
| **P (m)** | 6.6 | 5.5 | 4.7 | 4.1 | 3.7 | 3.3 | 3.0 |
| **$W_i$ (m)** | 3.8 | 3.2 | 2.7 | 2.4 | 2.1 | 1.9 | 1.7 |
| **$W_o$ (m)** | 3.2 | 2.7 | 2.3 | 2.0 | 1.8 | 1.6 | 1.4 |
| **$B_o = B_i$ (m)** | 4.4 | 3.6 | 3.1 | 2.7 | 2.4 | 2.2 | 2.0 |
| **B (m)** | 17.5 | 14.6 | 12.5 | 10.9 | 9.7 | 8.7 | 7.9 |
| **Volume of concrete ($m^3$) – T = 0.2 m** | 267 | 223 | 191 | 167 | 149 | 134 | 122 |
| **$C_{dw}$ for H = 2 m** | 1.56 | 1.39 | 1.26 | 1.14 | 1.05 | 0.97 | 0.90 |
| **Q ($m^3$/s) for H = 2 m** | 685 | 611 | 554 | 502 | 461 | 427 | 397 |

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