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HYDRAULIC CAPACITY IMPROVEMENT OF EXISTING SPILLWAYS – DESIGN OF PIANO KEY WEIRS *

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1. INTRODUCTION

With the increase of hydrological data records and the development of new methodologies for flood discharge estimations as well as higher requirements of the society with regard to safety issues, a large number of existing dams require spillway rehabilitation, in order to improve their hydraulic capacity.

* *Augmentation de la capacité hydraulique d'évacuateurs de crue existants – Dimensionnement des déversoirs en touches de piano.*

As in many other countries, some dams in France have spillway capacities which are too small compared to updated design floods. Among these dams, more than 160 are owned by *Electricité de France* (EDF) with an average age of approximately 50 years. Thus most of their spillways have been designed with short hydrological records only.

Improving spillway discharge capacity has therefore become a significant issue for EDF. Currently several projects to increase dam spillway capacity are under way. Cost associated with these projects can be significant since:

- the modification of the spillways has an important impact on the dam structure by removing significant quantities of concrete or adding new loads to existing structures (gate heightening for example)
- the energy dissipation structures are significant
- the energy production can be reduced during construction works

Amongst the possible solutions of spillway rehabilitation, the design of a new type of labyrinth weir, called Piano Key Weir (PKW), is often studied [1, 2] and has also been considered for EDF rehabilitation projects over the last years [3, 4, 5]. As for labyrinth spillways, the advantage of PKWs is the increase of the total effective crest length for a given width [6]. Consequently, it can be used to increase the discharge capacity for a given head or decrease the head for a given discharge. Therefore the implementation of such a spillway allows a high crest level which can also increase the storage capacity in the reservoir. In addition, beyond economical considerations, PKWs are free flow spillways and have a high level of safety and reliability. Moreover floating debris will easily pass over as the water level increases [7]. A key advantage of PKW structures is that they can be placed on the crest of most existing or new gravity dams, unlike traditional labyrinth weirs.

This paper presents four different dam rehabilitation projects of EDF, where the selected solution is based on the implementation of PKWs. During the design stage, seven different types of PKWs have been studied and their behaviour is presented. Furthermore, the discharge rating curves, based on the loss of effective crest length with the increase of the upstream head is proposed. Finally, structural considerations are presented concerning the stability of the new structures on the existing dams.

2. GENERAL CHARACTERISTICS OF PIANO KEY WEIRS

The new spillway shape, which looks like piano keys and which is an innovative alternative to labyrinth weirs, has been developed by Hydrocoop (France) in collaboration with the Laboratory of Hydraulic Developments and

Environment of the University of Briska, in Algeria and the National Laboratory of Hydraulic and Environment of EDF (EDF-LNHE). Differently from traditional labyrinth weirs, the bottom and lateral walls are partly rectangular and partly inclined, which increases the stability of the structure. Furthermore, the reduced base area facilitates the implementation on the crest of the existing dams.

The flow behaviour compared to the conventional labyrinth structures is quite different. The flow is divided in two parts, one from the inlet of the PKW that overflows as a thin screen and another from the outlet, which flows as a jet at the bottom [7].

As presented in [4], the total discharge over a PKW is function to several parameters which can be summarized as follows:

$$Q = f(\rho, g, \nu, H, L_T, P, W, a, b, B, S_{in}, S_{out}, t, R, \alpha)$$

where the fluid is characterized by its density ρ and the kinematic viscosity ν, g is the gravity acceleration and H the total water head. The other parameters are related to the geometry of the PKW. L_t is the total developed crest length, a and b are the inlet and outlet alveoli widths, B the length of the side weir, S_{in} and S_{out}, the inlet and outlet alveoli slopes, t the wall thickness, R the radius of crest curvature, and α the labyrinth angle. Fig. 1 illustrates the principal parameters of the typical design of a PKW.

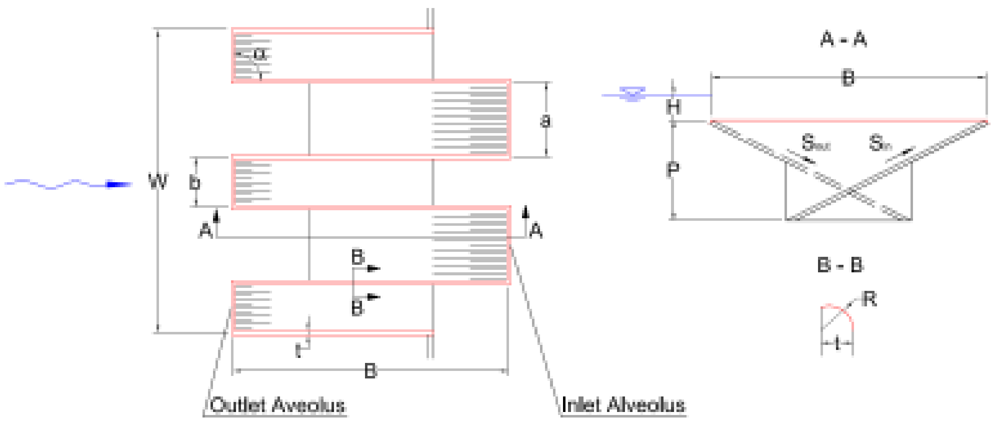


Fig. 1

Layout of the PKW with its main geometrical parameters.

Plan view (left), Sections A-A and B-B (right)

Composition du PKW avec ses principaux paramètres géométriques.

Situation (Gauche), Coupe A-A et B-B (Droite)

3. EDF REHABILITATION PROJECTS

The following sub-chapters describe EDF rehabilitation projects where PKWs have been considered for increasing the capacity of the existing spillway system. A summary of the main related geometrical characteristics is presented in chapter 4.1.

3.1. GOULOURS DAM

Goulours dam, owned by EDF is a 21 m high concrete arch gravity dam with a single curvature and a 71 m long crest. It was built between 1942 and 1946 on the Lauze and Riou Rivers (near Ax-les-Thermes, France).

The dam was designed with a one gated spillway, 4 m wide and 4 m high, in the centre of the dam. This gate controls a Creager type crest weir and is equipped with a floating device. The crest of the spillway is located at elevation 1076.0 m NGF. Normal operation level is situated at 1080.0 m NGF and the maximum operation level 1.0 m above, at elevation 1081.0 m NGF.

The first results of physical modelling performed in 2003 at EDF-LNHE (scale 1/20) confirmed that the overall discharge capacity of the existing gate is 92 m^3/s with a 1.0 m head. The update of the hydrological studies at Goulours resulted in a design flood at 162 m^3/s. A significant increase of the spillway capacity of 70 m^3/s was therefore required (increase by 75% of the existing capacity). Amongst the possible solutions (increasing the maximum operation level, new gated spillway, installation of fusegates, standard Creager free flow spillway or standard labyrinth spillway), the PKW revealed to be the most efficient and the cheapest.

For topographical reasons, it was decided that the PKW should be installed on the right dam abutment where access was easy (Fig. 2). In addition, a tailrace channel had to be excavated to take the water flow away from the toe of the dam. The PKW crest level was settled 5 cm above the current normal operation level. The automatic floating device is supposed to control the gate opening to maintain the normal operation level as long as possible. When the water level will reach the PKW crest, the existing gate will be fully opened. The related discharge capacity corresponds to a 25 years return period flood. This means that the PKW will only be used in the case of major events.

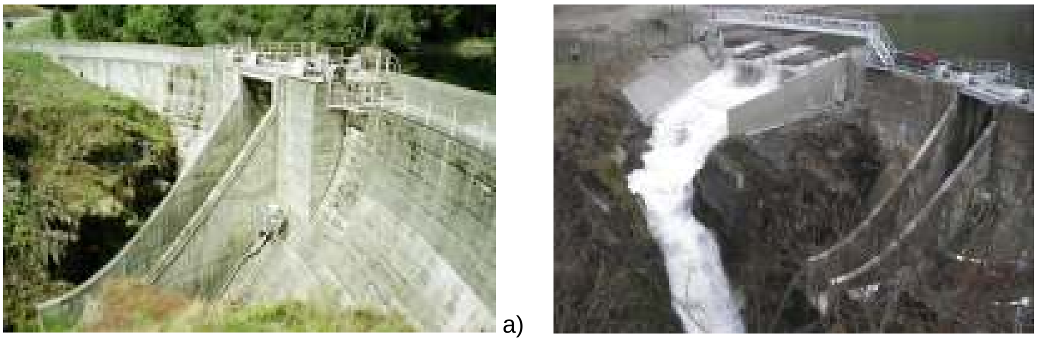

a) b)

Fig. 2
Downstream view of the Goulours Dam before (a) and after the construction of the PKW on the right abutment (b)
Vue aval du barrage de Goulours avant (a) et après la construction du PKW à l'appui droit (b)

The PKW of Goulours was constructed during summer 2006 and is probably the first realisation of such a spillway on an existing dam. The PKW was successfully tested in December 2006. The overall construction of Goulours PKW cost no more than 350'000 € and the construction planning was maintained. The Goulours hydro power plant was put in operation on time. Detailed design and construction particularities of the Goulours PKW are presented in [8].

3.2. ST-MARC DAM

St-Marc Dam is a 40 m high concrete gravity dam built between 1926 and 1930. The dam, located near Limoges (France) on the Taurion River creates a 150 ha reservoir, with a volume of 20 Mio m^3. It is currently equipped with two gated spillways, one 7.5 m wide on the right bank and the other with two sluices of 10.0 m wide in the centre of the dam which can evacuate a total discharge of 623 m^3/s. The normal operation level is 282.0 m NGF and the maximum operation level is 1.5 m above, at elevation 283.5 m NGF. A detailed description of the hydraulic scheme is presented in [4, 5]. The update of the hydrological studies based on the Gradex method [9] defined the designed flood as 750 m^3/s, so an increase in the spillway capacity of about 20% was required.

The EDF rehabilitation project is based on a 15 m wide PKW installed near the right bank between the existing spillways. The crest of the structure is fixed 15 cm above the normal water level (282.15 m NGF). Therefore the maximum relevant water head of PKW is 1.35 m. The three existing sluice gates will fully operate when the PKW starts to evacuate. This occurs for an incoming flood higher than 380 m^3/s, corresponding to a 50 years return period flood.

The initial design by EDF-CIH of Saint-Marc PKW was based on the experiments led by [6] and EDF-CIH experience from the Goulours PKW. For this project, a rectangular and a trapezoidal shape of PKW were considered and the hydraulic tests (scale 1/30) were carried out at the Laboratory of Hydraulic Constructions (LCH) at the *Ecole Polytechnique Fédérale de Lausanne* (EPFL), Switzerland. In order to integrate the PKW on the existing dam, an energy dissipation system with an inclined gutter [5] was designed. Fig. 3 presents downstream views of the model (a) and 3D CAD (b).


a)

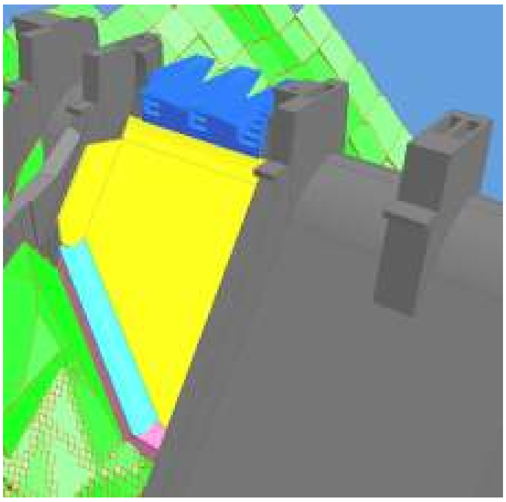

b)

Fig. 3
Saint-Marc PKW hydraulic model with the PKW and the energy dissipation system (a) and 3D CAD view (b)
Modèle réduit hydraulique de Saint-Marc avec le PKW et le système de dissipation d'énergie (a) et vue 3D CAO des ouvrages (b)

Construction works started during the summer of 2008. The overall construction cost estimation is approximately 1.6 Mio. €.

3.3. Les Gloriettes Dam

Les Gloriettes Dam was built between 1949 and 1951. The concrete arch dam is located in the Pyrenees near Gèdre (France) on the Gave d'Estaubé River. The present evacuation system is constituted of four free flow sluices at the top of the dam (crest elevation 1667.0 m NGF) and the capacity is about 80 m^3/s at the maximum operation level (1667.8 m NGF). For a design flood of 1000 years return period, a discharge peak of 150 m^3/s has been calculated. Thus, the deficit of flood evacuation of the existing spillway is about 70 m^3/s.

To eliminate the overflow risk, a PKW will be added to the right bank of the dam, replacing part of the gravity dam, which insures the foundation stability. To guarantee a safe evacuation of the water from the new weir to the downstream river, a stepped channel with an intermediate stilling basin has been designed. Two different PKW projects, one with 4 outlets and the other with 7, have been projected and tested by means of physical model (scale 1/30) at the LCH/EPFL, taking into account the geometrical and hydraulic upstream and downstream conditions. The weir crest is at 1667.0 m NGF which is the same level as the existing spillway. Fig. 4illustrates downstream views of the existing dam (a) and the modelled PKW with 4 outlet alveoli (b).

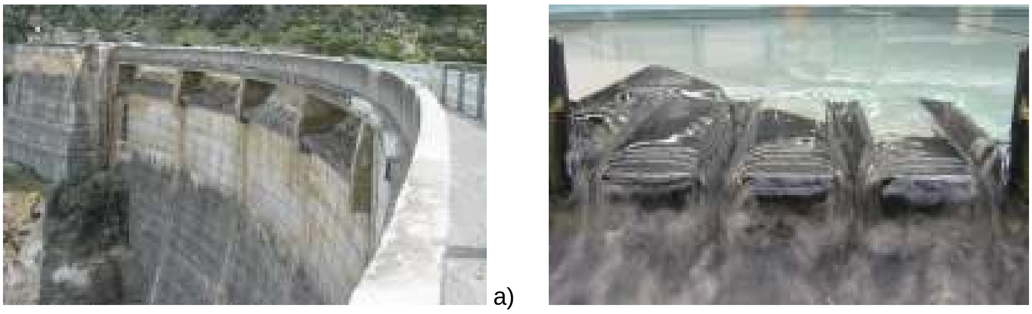

a) b)

Fig. 4
Downstream views of the existing dam (a) and of the modelled PKW (b)
Vues aval du barrage existant (a) et d'un PKW modélisé (b)

3.4. ETROIT DAM

Etroit Dam is a 25 m high concrete gravity dam whose construction was achieved in 1933. The dam is located on the Taurion River, upstream the aforementioned Saint-Marc dam. It has currently two gated spillways located on the right bank of the dam, one 8.5 m wide on the right hand side and the other one 9.0 m wide. Both gates can evacuate a total discharge of 456 m^3/s. The normal operation level is at elevation 328.0 m NGF and the maximum operation level situated 1.0 m above, at elevation 329.0 m NGF.

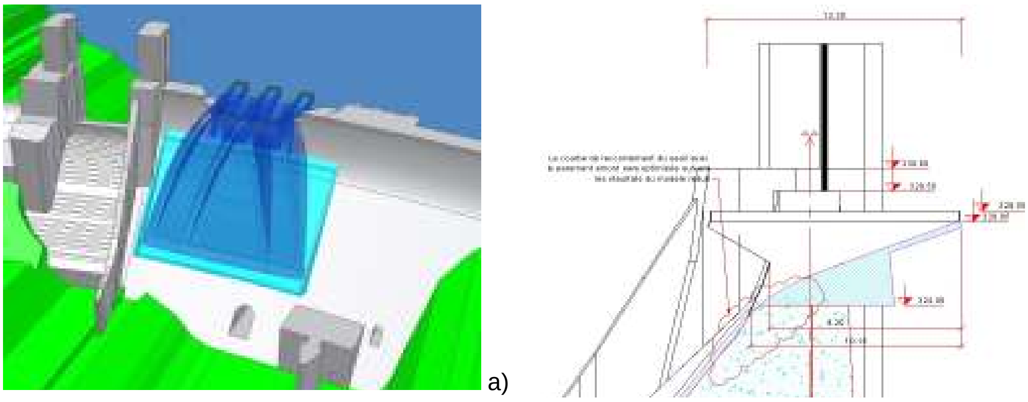
The update of the hydrological studies based on the Gradex method defined the designed flood as 570 m^3/s. The additional needed capacity is however approximately only 75 m^3/s due to the fact that the upstream Roche-Talamie dam is able to partially attenuate floods.

Etroit dam is located in a remote area the access of which is potentially difficult during heavy rains or extreme climate events (roads and tracks winding through sloped forests). Therefore the solution chosen by EDF was mainly based on reliability and operation safety aspects. From this point of view, an additional PKW clearly improves the overfall reliability of the spillway system.

The EDF rehabilitation project is thus based on a 11.7 m wide PKW installed along the axis of the river between the existing spillways and bottom outlets. The crest of the PKW is fixed at the normal water level 328.0 m NGF. Therefore the maximum relevant water head of PKW is 1.0 m. The design of the Etroit PKW was significantly improved compared to Goulours and Saint-Marc as well as Les Gloriettes solutions:

- The ratio L_t/W is 6.6 while it was less than 6 for the other projects.
- The axis of the PKW was slightly shifted upstream to increase the overall stability and improve approach flow conditions.
- The developed PKW crest was heightened by a 50 cm vertical wall.

The physical modelling was carried out at the Laboratory of Sogreah (France) at a geometrical scale of 1/30. Fig. 5 illustrates a 3D CAD downstream view of the Etroit Dam with the designed PKW (a) and a cross section of an outlet alveoli (b). Construction works of the PKW will start in the summer of 2009.



a) b)

Fig. 5

3D CAD view of the new PKW spillway (a) and a section of PKW outlet alveoli (b)

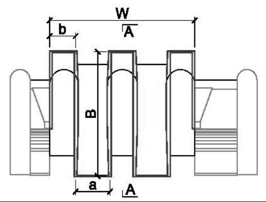
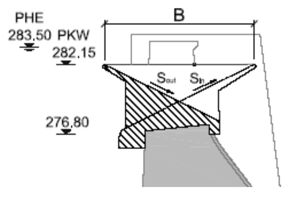
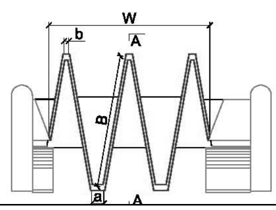
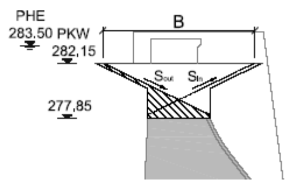
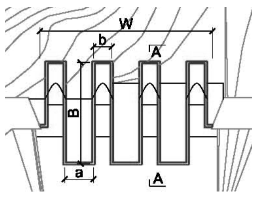
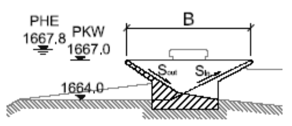
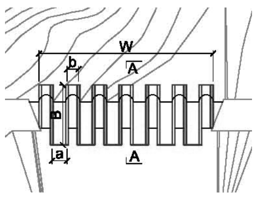
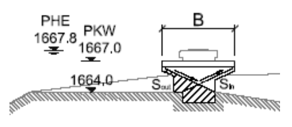
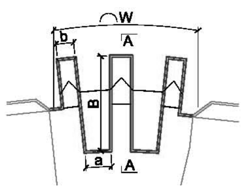
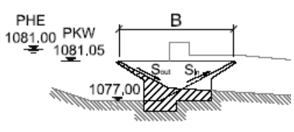
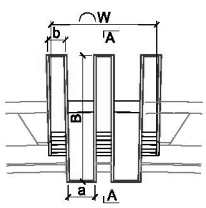
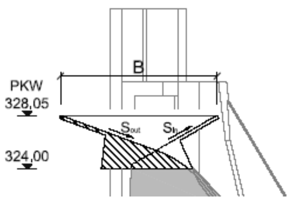
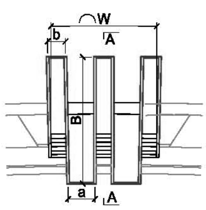
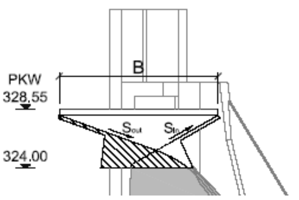
Vue 3D CAD du nouveau PKW (a) et coupe sur une alvéole de sortie (b)

4. EXPERIMENTAL RESULTS

4.1. LAYOUTS

Table 1 shows the different layouts of the tested PKWs with a summary of their main geometrical characteristics.

Table 1
Layout and geometrical parameters of the tested PKWs
Configurations et paramètres géométriques des PKWs testés

	Situation (flow direction ↓)	**Cross Section A-A** Outlet Alveolus	L_t [m]	W [m]	a [m]	b [m]	B [m]	S_{out} [-]	S_{in} [-]
St-Marc I			77.0	15.6	3.45	2.45	12.1	0.49	0.49
St-Marc II			68.5	14.4	1.3	0.6	12.9	0.49	0.49
Les Gloriettes I			86.8	16.5	2.75	1.75	9.9	0.48	0.60
Les Gloriettes II			93.1	16.7	1.45	1.10	5.7	0.47	0.47
Goulours			59.0	11.0	2.45	2.00	9.3	0.51	0.51
Etroit I			77.9	11.7	2.70	1.75	12.3	0.58	0.37
Etroit II			77.9	11.7	2.70	1.75	12.3	0.58	0.37

4.2. DATA ANALYSIS

The following is based on experimental data of the physical modelling tests on the PKWs described in Tab. 1. As the individual layouts show quite different and particular geometrical characteristics, a qualitative approach has been chosen to analyse the results. For a detailed analysis of the influence of each specific parameter on the hydraulic capacity of the weir, additional systematic tests should be performed. However, two basic curves allow highlighting the flow characteristics:

- The specific capacity curve q_L as a function of H with $q_L=Q_{PKW}/L_t$ based on the total crest length (Fig. 6).
- The specific capacity curve q_w as a function of H with $q_W=Q_{PKW}/W$ based on the total crest length (Fig. 7).

For the analysis of the specific capacity based on the total crest length, the PKWs' behaviour is plotted in comparison with a linear sharp-crested weir, assuming a constant discharge coefficient C_d=0.42 [10].

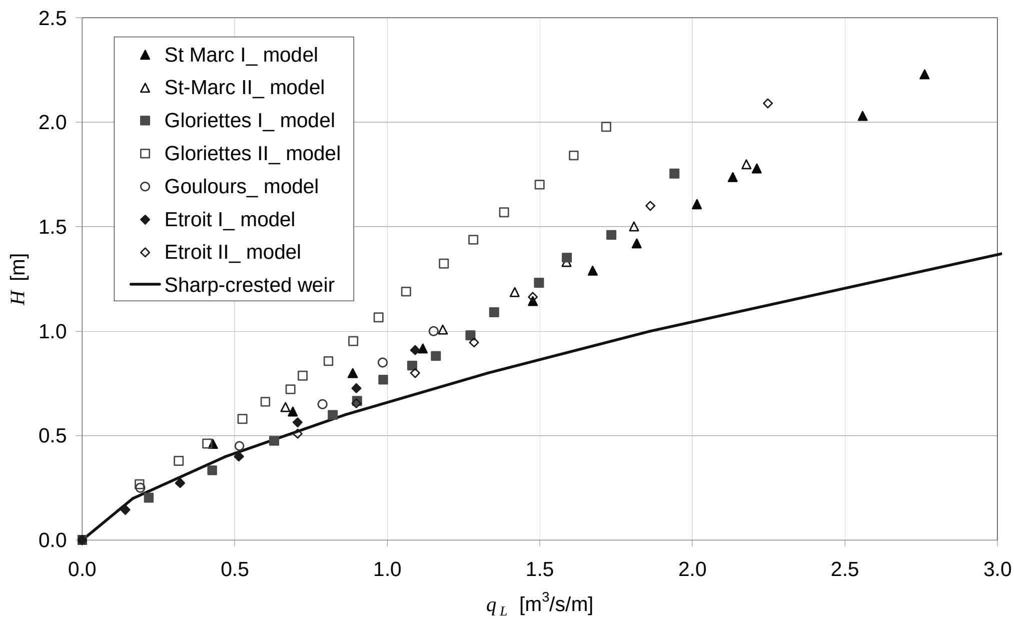


Fig. 6

Measured heads for specific flows over the developed length L_t of the weir

Charges mesurées pour différents débits spécifiques sur la longueur de crête L_t du déversoir

From Fig. 6, the following comments can be highlighted:

- For low heads (up to approximately 2 to 3 cm on the model), the overflowing jet sticks at the lateral walls of the PKW originate a suction effect, which increases the discharge. This scale effect is confirmed by the model results of Gloriettes I and Etroit I and II, where the PKWs reveal higher discharges than a sharp-crested weir with a total crest length L_t.
- The effect of high outlet alveoli slopes S_{out} is important at low heads when the water can freely flow. With increase at head, the upstream part of these alveoli starts drowning, leading to a loss of the effective crest length.
- The effect of the widths of the outlet alveoli b is clearly shown by the small specific discharge q_L of Gloriettes II compared to other models. In fact, with increasing head, a lateral jet overcrossing occurs, which decreases the efficiency of the PKW related to its total crest length L_t. The greater the value of b, the later (with H increase) this phenomenon occurs.
- St-Marc II is the only tested structure with a horizontal angle α different by 90° (80°). It presents a lower specific discharge t han St-Marc I for reduced heads H, due to its small value of b. In this case, the upstream part of the outlet alveoli has a small contribution in the total discharge. Nevertheless, both approach each other when the head increases. The reason of this behaviour is that jet overcrossing occurs later in the downstream part of the PKW for St-Marc II.
- The positive effect of the raised wall installed along the total crest length of the Etroit PKW can clearly be seen. With head increase, Etroit II shows higher specific discharge. Raised walls delay the flow submergence at low heads. This feature increases the PKW capacity by approximately 15%. The effect of the raised wall could not be studied for Gloriettes II because no measurements have been performed without this feature.

For the specific discharge q_w, the models are compared to a broad crested weir with a constant discharge coefficient of C_d=0.34, as suggested by [10] (Fig. 7). The reference to a broad crest weir is based on the assumption that the PKW will progressively tend to a similar behaviour with increasing head.

From Fig. 7, the following can be observed:

- Etroit II has a higher specific discharge related to the sluice width. This behaviour is mainly due to its important dimensions and the presence of the raised wall.
- As discussed above, the small value of b reduces the capacity of the Gloriettes II model. Even if this model has an important ratio L_t/W=5.6, it has the lowest specific discharge.

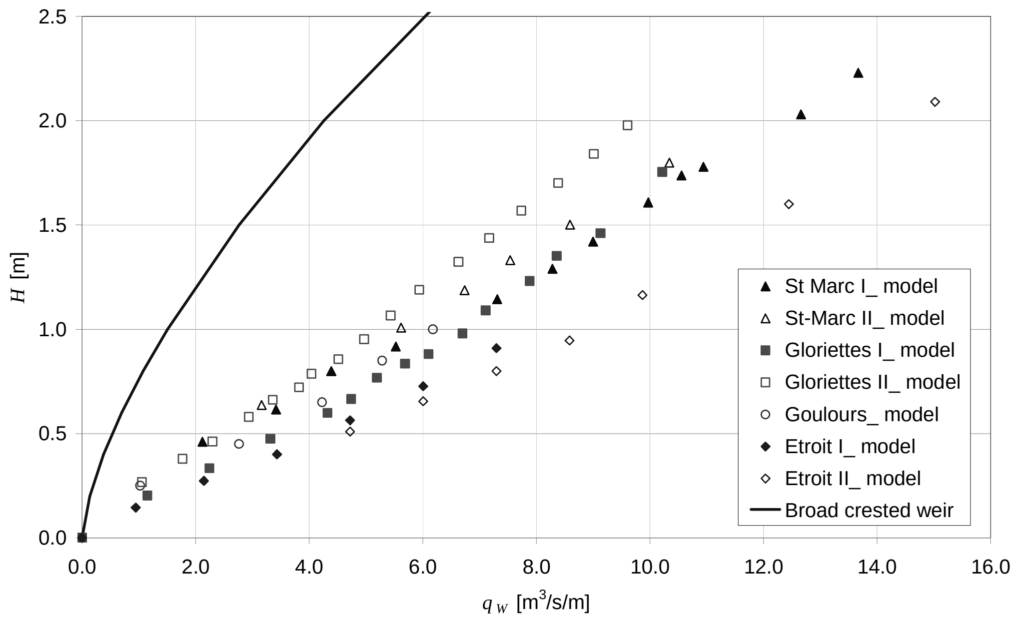


Fig. 7

Measured heads for different specific flows over the width (W) of the weir

Charges mesurées pour différents débits spécifiques sur la largeur du déversoir (W)

4.3. CONCEPTUAL MODEL FOR THE HYDRAULIC CAPACITY

Based on the experiments performed with the different PKWs, a conceptual model based on the effective crest length is proposed for fitting the different capacity curves. The adjustment of the curves for the tested PKWs is based on the classical equation of a linear crest weir:

$$Q = C_d L \sqrt{2g} H^{\frac{3}{2}} \tag{1}$$

The PKW is considered as a linear crest weir with an effective length (L_{eff}) decreasing with the increase of the head. The variation of L_{eff} related to H can be adjusted with a function $f(x)=1/x^n$. Thus, using the magnification aspect L_{eff}/W, Eq. (2) is proposed to fit the variation of L_{eff}. This equation, slightly modified from [4] is characterized by the presence of a corrector term tending towards zero with increasing head.

$$\frac{L_{eff}}{W} = 1 + \frac{1}{\left(\frac{H}{W} + \frac{1}{\sqrt[n]{\frac{L_t}{W} - 1}} \right)^n} \tag{2}$$

Using Eq. (2), Eq. (1) can be written as:

$$\frac{Q}{W} = C_d \frac{L_{eff}}{W} \sqrt{2g} H^{\frac{3}{2}} \tag{3}$$

According to Eq. (3), $C_d\, L_{eff}/W$ as a function of H is presented graphically in Fig. 8 for the different cases studied.

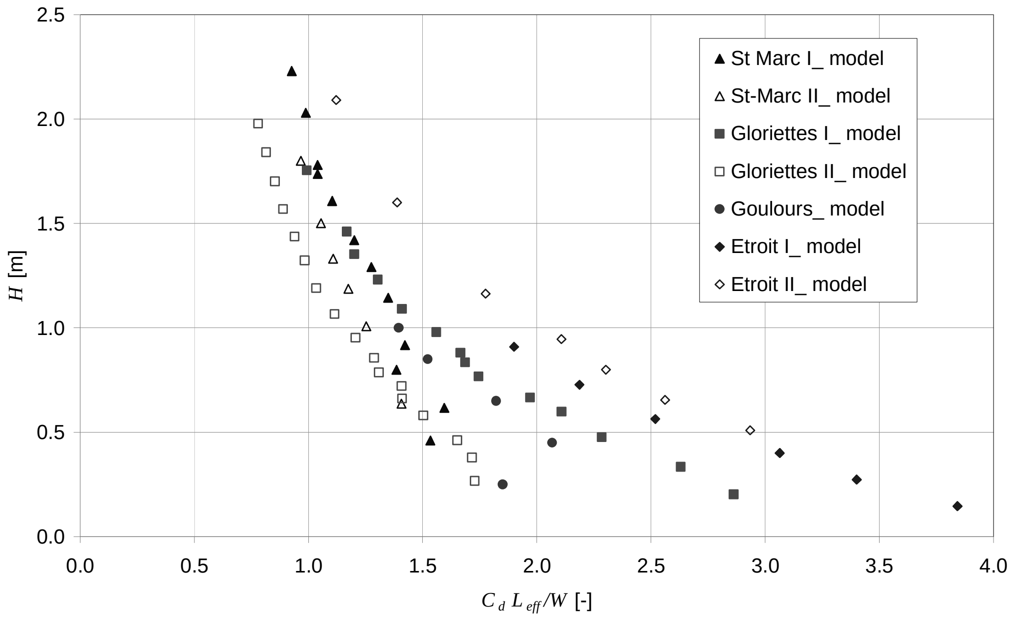


Fig. 8

$C_d\, L_{eff}/W$ as a function of *H* for the different tested PKWs

$C_d\, L_{eff}/W$ en fonction de H pour les différents PKWs testés

In order to fit the different curves, the discharge coefficient C_d and the exponent n of Eq. (2) have been adjusted. Table 2 presents the values obtained for the different PKWs.

Table 2

Discharge coefficient C_d and exponent *n* for the different models tested

Coefficient de debit C_d et exposant n pour les différents modèles testés

Model	C_d	n	Model	C_d	n
St-Marc	0.42	7.5	Goulours	0.50	9.0
St-Marc II	0.42	7.8	Etroit I	0.55	9.0
Gloriettes I	0.55	14.5	Etroit II	0.60	9.5
Gloriettes II	0.42	13.8			

The adjusted capacity curves of the different PKWs using the corrected C_d and *n* values are presented in Fig. 9 for the models of St-Marc I and II and Gloriettes I and II and in Fig. 10 for the models of Goulours and Etroit I and II. It is important to note that the discharge coefficient values for some models is higher than the average value for sharp-crested weirs (C_d=0.42). This is function to different parameters like the approach channel configuration or the crest shape. Thus, additional systematic analysis has to be performed in order to explain the discharge coefficient and the exponent *n* as function of the geometrical characteristics of the PKWs.

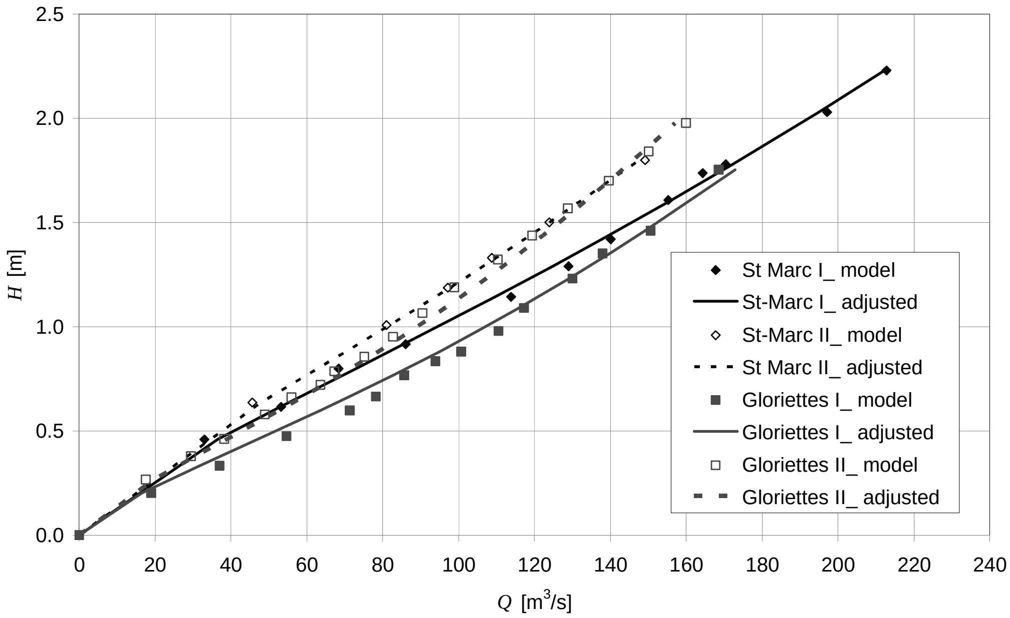


Fig. 9

Adjusted capacity curves and measured points for the PKWs of St-Marc I and II and Gloriettes I and II

Courbes de capacité ajustées pour les PKWs de St-Marc I et II et Gloriettes I et II

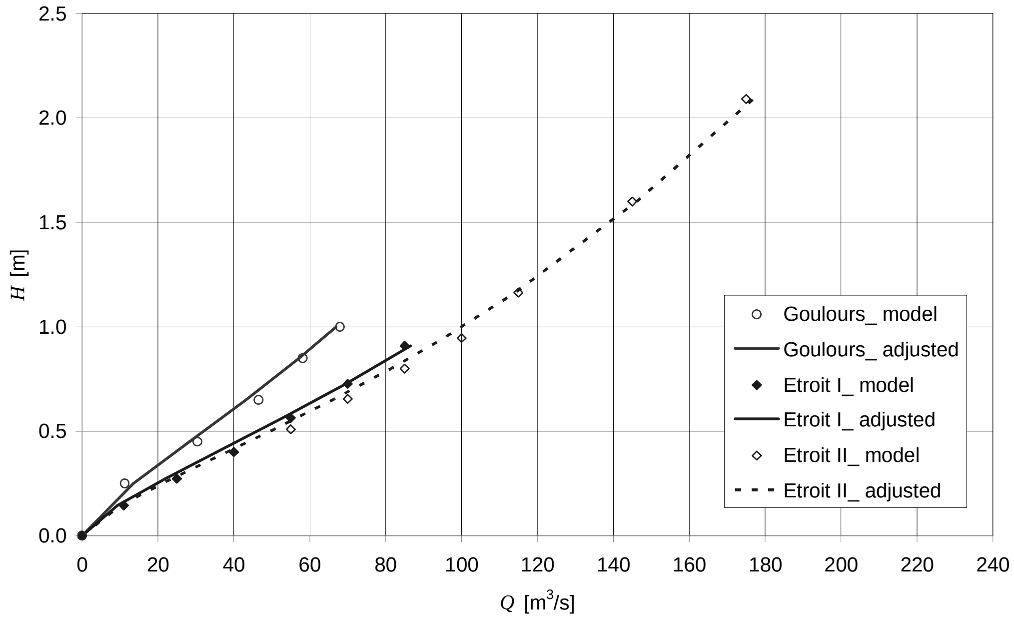


Fig. 10

Adjusted capacity curves and measured points for the PKWs of Goulours and Etroit I and II

Courbes de capacité ajustées pour les PKWs de Goulours et Etroit I et II

4.4. SUMMARY OF THE RESULTS OF THE REHABILITATION PROJECTS

- Goulours: The PKW has the capacity to evacuate 68 m^3/s at the maximum operation level. This means that the total hydraulic capacity of the spillway is 157 m^3/s.
- St-Marc: The model I has been adopted for the project. It has a capacity of 134 m^3/s for the maximum operation level condition. Considering the present stage (623 m^3/s), the total capacity of 757 m^3/s will be higher than the design discharge (750 m^3/s).
- Les Gloriettes: The model I has been adopted. The discharge capacity of this PKW at the maximum operation level is 90 m^3/s. Considering that the current capacity is 80 m^3/s, the total capacity will be 170 m^3/s, significantly higher than the design capacity of 150 m^3/s.
- Etroit: For the Etroit's project, the PKW with the raised wall (Etroit II) was adopted. The total capacity at the maximum operation level of this spillway is 100 m^3/s, that is to say, 25 m^3/s higher than the required additional discharge. The total capacity will then be 556 m^3/s.

5. STRUCTURAL ASPECTS

5.1. PROTECTION OF EXISTING STRUCTURES

Energy dissipation downstream of a new spillway is a critical issue since it might endanger dam safety and increase costs significantly.

The water evacuated by a PKW is related to particular problems on the downstream face of the dam. Velocities above 20 m/s and unusual impact angles of 25° are often the cause of cavitations, cracks, development of turbulences and uplift pressures and can reduce the safety of the existing structures. Old dams like St-Marc and Etroit often show a poor quality of the concrete of the downstream face with a low content of cement and poor surface characteristics. It is consequently advised to protect the downstream face of the dam with a 50 cm thick concrete protection slab at the minimum. This protection slab should also be drained in order to limit dynamic uplift.

5.2. PKW STABILITY

Without water loads, PKW structures are self-balanced with upstream and downstream cantilever slabs. Water loads will bring destabilizing loads, which are moderate compared to gravity stabilizing loads. Therefore, usual PKW only require a few anchors to ensure overall stability. With a suitable design, it is even possible not to have any anchors at all. This performance was achieved with the Saint-Marc PKW by adding a counterweight beam upstream of the entrance of the inlet.

Even if the area has a reduced seismic activity, the seismic amplification factor on the crest dam can be more than 4. Ice loads also have to be taken into account because of the particular shape of PKWs, especially in mountains or cold regions. Whatever the dam, a minimum ice layer thickness of 30 cm is generally taken into account in France with ice loads of 15 t/m^2 [11].

Internal stability of PKW will depend on the choice of the material. PKWs can be constructed in reinforced concrete, steel, or other mixed materials. Thickness of reinforced concrete walls is an issue. If the available space is sufficient to install the PKW, 35 cm thick walls (rather than 20 cm for Goulours) will reduce reinforcement quantity, improve concrete durability through concrete cover increase, increase PKW stiffness and improve structural response to dynamic loads coming from water flow vibrations, and make construction on site easier. Whenever PKWs should be built in steel, a special emphasis should be given to the potential vibrations of the structure.

6. CONCLUSIONS AND RECOMMENDATIONS

Over the last years, the need of spillway rehabilitation is subject of many projects worldwide. Amongst the solutions for this problem, the implementation of a new type of labyrinth spillway, called PKW (Piano Key Weir) has been considered by EDF for increasing the spillway capacity of their dams. When compared with other solutions, the PKW has a number of advantages:

- no change of normal and maximum operating levels
- minor impact on dam structure
- no impact on existing gate and other mechanical components
- reliability of free flow spillway, requiring little maintenance
- low cost solution involving the construction of simple concrete units

From the analysis of seven different PKW shapes, the following general conclusions can be highlighted:

- For increasing head, the absolute hydraulic capacity grows, but the relative capacity decreases, as shown by comparison with a broad crested weir.
- At low heads (near 0 m) the PKW behaves like a sharp-crested weir with crest length L_t. For increasing heads, its behaviour is close to that of broad crested weirs of width W.
- For high heads, strait outlet alveoli have an increasing effect of lateral jets overcrossing, which reduces the capacity. In this case, important values of *b* are an advantage. A weir layout with an important number of short and thin alveoli, and therefore many angles is not recommended.

It is important to note that this analysis is based on particular PKW configurations. For a detailed non-dimensional analysis of the influence of a specific parameter on the hydraulic capacity of the weir, systematic tests should still be performed.

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SUMMARY

Over the past few decades, labyrinth weir spillways have been constructed worldwide. They are normally designed to increase the total effective crest length for a given sluice width but their application is sometimes difficult in dam rehabilitation projects due to inappropriate supporting conditions.

To solve this problem, a new concept of labyrinth spillways called Piano Key Weirs (PKW) has been developed by Hydrocoop (France). This innovative alternative provides an increase in the stability of the structure compared to standard labyrinth weirs and can be placed on the top of most existing or new dams.

A conceptual approach for the design of PK-weirs based on the loss of the effective length with the increase of the upstream head is presented. The analytical approach is calibrated by experimental results of seven PKW shapes tested on hydraulic models at the Laboratory of Hydraulic Constructions (LCH) of the *Ecole Polytechinique Fédérale de Lausanne* (Switzerland), at the National Laboratory of Hydraulics and Environment of the *Electricité de France* (France) and at Sogreah Laboratory (France) in the framework of four dam rehabilitation projects of EDF. In addition, structural considerations are presented concerning the stability of the PKW.

RÉSUMÉ

Au cours des dernières années, plusieurs déversoirs en labyrinthes ont été construits dans le monde. Ces structures sont utilisées pour augmenter la longueur de crête déversante sur une ouverture donnée. Dans les projets de réhabilitation de barrages existants, l'application d'une telle structure est souvent difficile en raison de la place disponible limitée pour sa fondation.

C'est pourquoi un nouveau type de déversoir a été développé récemment par Hydrocoop en France – le Piano Key Weir (PKW). Cette solution alternative se caractérise par un débit spécifique particulièrement élevé, capable d'augmenter l'efficacité du contrôle des crues sur des barrages existants, en déficit de capacité.

L'article présente une approche, pour la conception et le dimensionnement d'un PKW. Il est basé sur la perte de longueur effective avec l'augmentation de la charge. Le développement analytique est validé par les résultats d'essais sur modèles effectués au Laboratoire de Constructions Hydrauliques (LCH) de l'École Polytechnique Fédérale de Lausanne (Suisse), au Laboratoire National d'Hydraulique et Environnement d'Électricité de France (France) et au Laboratoire de Sogreah (France) pour quatre projets de réhabilitation de barrages existants exploités par EDF. Une dernière partie est consacrée aux considérations sur la stabilité des PKWs.