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Design of a new economic shape of weir

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ABSTRACT: Reservoir dams are often confronted with two fundamental problems, the first relates to the control of floods, which can present overtopping risk, the second relates to the loss of the storage capacity as a result of sedimentation. The control of floods is assured with spillways, which assure the passage of floods without incident. Nevertheless, its cost represents a significant part of global cost of dam. The loss of storage as result of sedimentation of reservoir can be remedied by heightening the sill of spillways which allows to have a supplementary space of storage. The search for an optimal shape of weir which possesses a high performance and a low cost, led to conception of a new shape of no linear weir. This new shape of weir baptized Piano Keys Weir (P.K. Weir) represent an effective alternative for most new dams and can increase at low cost the capacity of evacuation and\or storage of several existing dams. The results of experimental tests detailed on 23 physical models showed that two P.K. Weirs solutions can be selected. Application of P.K. WEIR for some Algerian dams allows to recover global storage volume about 250 $10^6 m^3$. The P.K. WEIR can be feasible for most earth dams and concrete dams, equipped with a free flow spillway. The realization of this type of weir for the increase of reservoirs capacity requires a low cost. Two examples of applications were made for Algerian dams.

1 INTRODUCTION

The mobilization of waters of surface is mainly assured by the reservoir dams; nevertheless, these works are confronted to two problems of fundamental importance. The first is referred to the risks of the insufficiency of the capacity of evacuation of the spillway and the second corresponds to the harmful effects of siltation. The reports on the incidents of rupture of the dams showed that almost a third of the accidents is related to the insufficiency of the capacity of the spillway. Consequently, the ICOLD (International Committee of dam) recommended the readaptation of a great number of spillways to ensure the safety of the dams. Consequently, the design engineers of the dams must choose design flood of greater period of return. This have for result of the spillways of width more important which exceeds the width of the existing weirs, which leads to construction of new spillways which will the raise cost of realization.

In order to reduce the cost of the spillways of the new dams and to make possible the readaptation of the spillways of the existing dams, the design engineers of the dams try to reduce total dimensions of the spillway and to simplify its construction, without affecting the degree of safety required. The solution which answers to these requirements is the design of a labyrinth spillway characterized by a crest with broken axis in plan which is quite agreed for cases where the width of the weir is limited by the topography of the terrain for the new dams or by the width of the existing weir in the event of readaptation of an existing spillway. The concept implies a work where the length of crest is developed by a configuration in broken line which generates a crest longer than the width of the weir. The labyrinth weir is characterized by a great capacity of evacuation under a relatively weak load contrary to the rectilinear weirs. This advantage includes the low cost of realization and maintenance in comparison with the rectilinear weirs and a more reliable exploitation compared with that of the gated weirs. Although the traditional shape cannot be placed in top of traditional gravity dams cross section.

A new shape of nonrectilinear weir baptized Piano Keys Weir (P.K. Weir) was developed by Hydrocoop France in collaboration with the Laboratory Hydraulic Developments and Environment of the University of BISKRA (ALGERIA). This new type of weir has the advantage to be applied also to gravity dams cross section. P.K. Weir allows the evacuation of specific flows up to 100 $m^3/s/m$, while multiplying at least by three the flow of a Creager weir, its construction is simple and easy and can be carried out by local resources of each country. The P.K. Weir will reduce considerably the cost of the majority of the new dams and will allow to improve at the same time, the capacity of evacuation of the spillway and the storage capacity of the reservoir of the existing dams.

2 GEOMETRICAL CONFIGURATION OF THE P.K. WEIR

On the basis of preliminary tests on physical small-scale models the geometrical form of P.K. Weir was defined by:

- A provision rectangular of the alveoli somewhat similar to the shapes of Keys of Piano, which explains the name of Piano Weir Keys (P.K. Weir).
- An inclined apron of the upstream and downstream alveoli, which favours the use of the overhangs.
- A reduced length of the base thanks to the use of the overhangs.
- A reduced width of the elements thanks to the rectangular form.
- A reduced surface of the side walls.

The variation of layout of the weir is possible; however, the most advantageous form corresponds to the rectangular symmetrical form shown in Figures 1 and 2 because it is easiest to build. The configuration of such a form in plan is defined by the height P, the width of the upstream and downstream alveoli, the length of the overhangs, the ratio length l/w, number of cycles, N, forming the weir, and the ratio of vertical aspect w/P.

Thus, the efficiency of P.K. Weir will be a function of the following parameters without dimensions: h/P, w/P, l/w, a/b, d/c. These parameters derive directly from the geometry of P.K. Weir and of the design head, they are thus of principal importance.

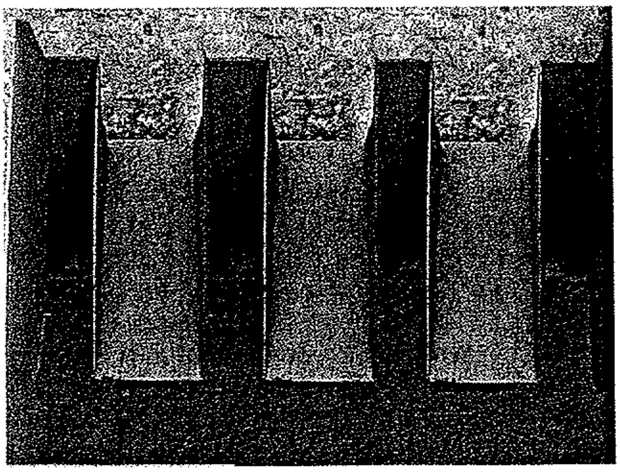

Figure 1. Piano keys weir (P.K.Weir).

P: maximum height of P.K. Weir
B: length of a side wall
a: width of the upstream alveolus
b: width of the downstream alveolus
c: length of the upstream overhang
d: length of the downstream overhang
W: width of the weir

The efficiency of P.K. Weir can be also affected by the parameters of secondary importance resulting from the details of construction, as the shape of entry under the overhangs, the section of the crest and the presence of the floating materials.

A systematic cover of the principal parameters and the secondary parameters most important were made in the experimental study.

3 PROGRAM EXPERIMENTAL

Experimental work was led in an experimental device of simulation of pool made up of a supply channel having a section 0.75 × 0.75 m and 4,30 m of length.

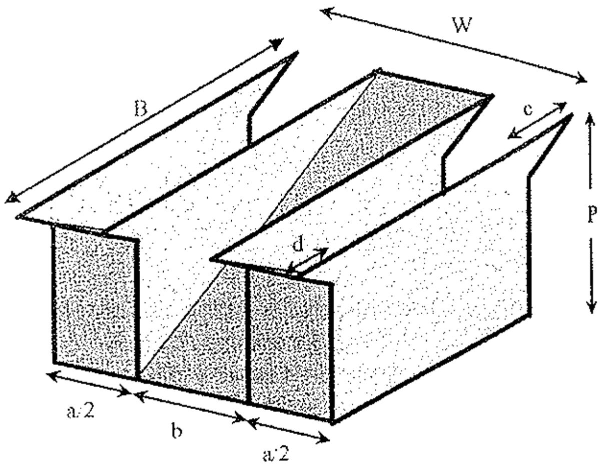

Figure 2. Diagram of an element of the Piano keys weir.

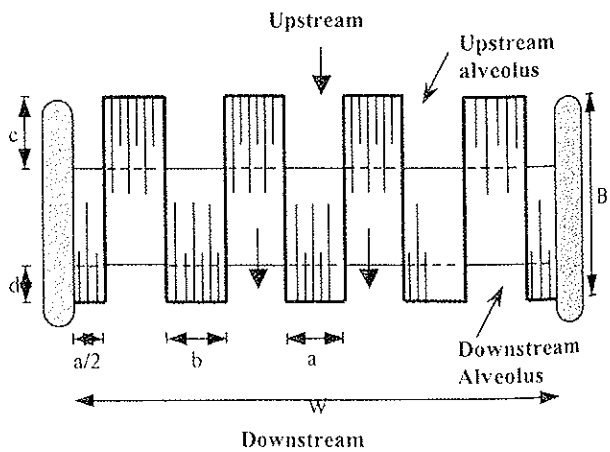

Figure 3. Layout of the Piano keys weir.

This channel is connected to a basin of simulation of pool having the form of a square 3 × 3 m and 1,1 m of height. The entry upstream of the basin of simulation of pool is equipped with a metal grid and a brick wall, which makes it possible to ensure a uniform flow. Series of pressure outlet are placed in the basin of simulation at various places making it possible to measure the water pressure in each point. The models of P.K. Weir are inserted to the outlet of basin of simulation. A restitution channel of length 2 m and of width 1 m is connected to the outlet of basin ensuring the role of a chute of spillway.

The models of P.K. Weir were built of steel of thickness 2 mm. Whole of the models is characterized by a shape of thin crest.

4 PRESENTATION OF THE RESULTS

To check the behavior and the performance of this new weir several tests detailed on selected forms were then carried out since the year 2002 at the Laboratory of Hydraulic Developments and Environment of the University of Biskra. The tests carried out on about thirty small-scale models of P.K. Weir gave a basis to optimize the increase in the discharge of P.K. Weir according to relationship's between the length, the height, the width and the shape of the elements, in particular according to the relationship between the length of the crest of P.K. Weir and its width N = L/W.

The capacity of evacuation of a non-linear weir is generally expressed by the coefficient of discharge, which derives of the universal equation, which expresses the flow, which passes through a weir:

$$Cw = \frac{Q}{W\sqrt{2g}h^{3/2}}$$

With:

Cw: coefficient of discharge
Q: flow which pass through the weir (m^3/s)
W: width of the weir (m)
h: height of the nappe (m).

The coefficient of discharge is given according to the couple of the measured values, the discharge (Q) and the head of water over the P.K. Weir (h), the other parameters of the equation (1) are constant for a given weir. For practical reasons, it is more suitable to represent the coefficient of discharge according to the adimensionals parameters.

$$C_w = f(\frac{D}{P}, \frac{W}{P}, \frac{L}{W}, \frac{b}{a}, \frac{c}{d}, \frac{h^*}{P}, \frac{t}{P}, \frac{R}{P})$$

Or:

h^*: total head on the sill of P.K. Weir
D: maximum downstream height of P.K. Weir
L: developed length of the weir

The total head corresponds to the piezometric height added to the kinetic head.

$$h^* = h + \frac{V^2}{2g}$$

4.1 *Mode of flow on P.K. Weir*

The flow on the P.K. Weir is completely different from the flow on the labyrinth weir, it is characterized by two discharging nappe, the first in the form of a jet of the bottom which flow along the inclined apron of the downstream alveolus and the second in the form of a screen more or less thin according to the load on the

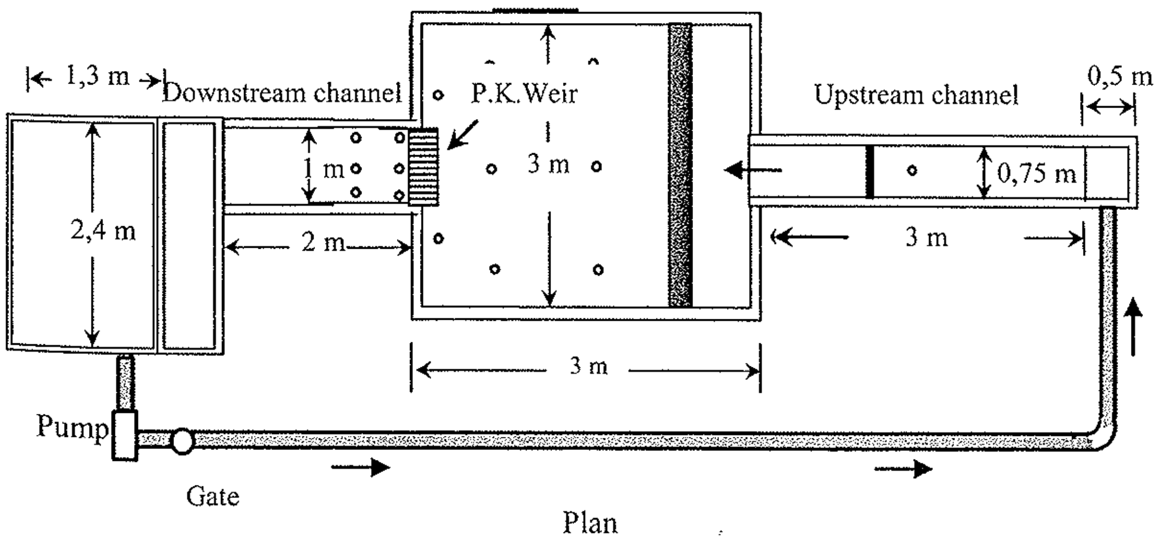

Figure 4. Layout of the experimental device.

Figure 5. Flow on the P.K. Weir.

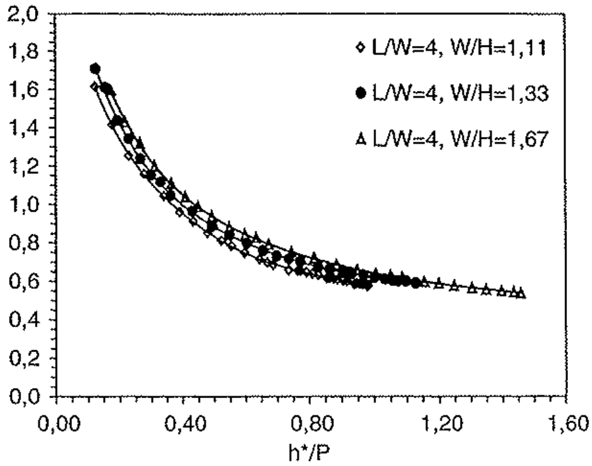

Figure 6. Coefficient of discharge according to the ratio of vertical aspect W/P.

weir. The second nappe which is superficial, favours the ventilation of the weir because of the presence of the overhangs (Fig.5).

4.2 *Ratio of the vertical aspect, W/P*

The ratio of vertical aspect which represents the vertical geometry can have two indications, the first reflects the effect of the height variation for a width of cycle fixes and the second indicates the influence of the variation of the width for a height of weir fixes. The results of the tests obtained on three models of same width of cycle and different height indicate that the coefficient of discharge of P.K. Weir is depend on parameter W/H. In other words, the capacity of evacuation is dependent of the height of P.K. Weir. The increase of the height of 20% increases the capacity of evacuation from 5 to 10% (Fig.6).

4.3 *Relative Length, L/W*

Generally, the ratio L/W which expresses the relationship between the total length of crest and the width of the weir influences the flow remarkably. The Figure 7 shows that the increase in the ratio L/W is very efficient for h/P < 0.6 but not for h/P close to 1.

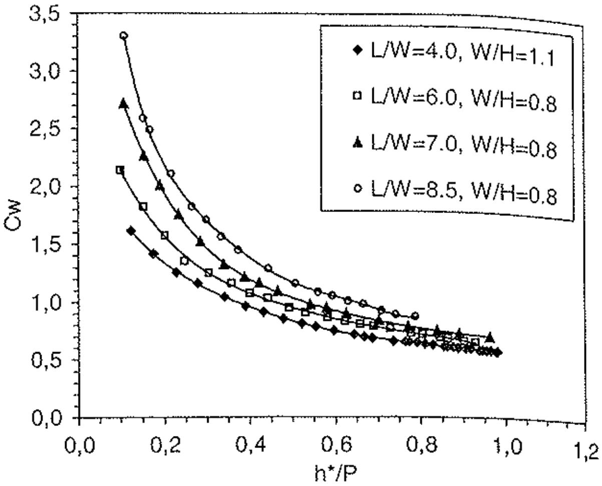

Figure 7. Coefficient of discharge according to ratio L/W.

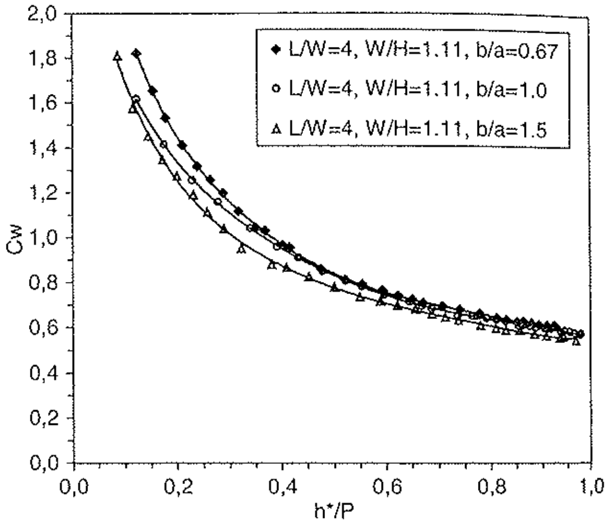

Figure 8. Coefficient of discharge according to the width of the upstream and downstream alveoli.

4.4 *Impact of the alveoli width*

The geometry in plan of P.K.Weir is characterized by two alveoli of rectangular form, the first of width (a) oriented towards the upstream and the second of width (b) directed towards the downstream.

The slope of the apron of the alveoli is dependent of the length of the overhangs and the height of the weir, so the flow in the upstream and downstream alveoli can be different.

To check the impact of the variation of the width of the alveolus three cases were considered (b/a = 0.67, 1.0 and 1.5).

The Figure 8 shows that the choice of the width of the upstream alveolus higher than that of the downstream

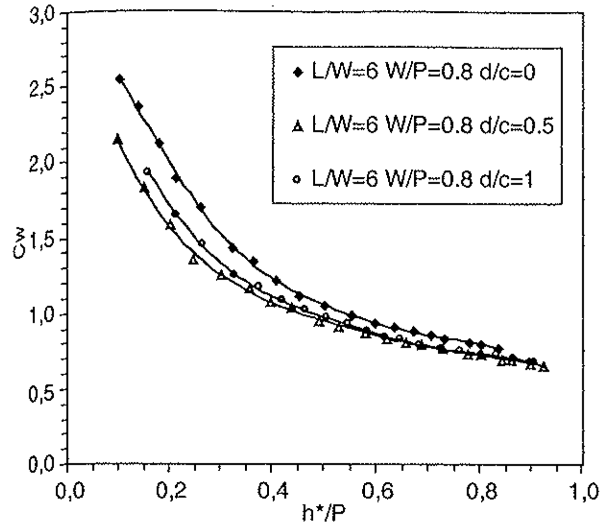

Figure 9. Coefficient of discharge according to the length of the overhangs.

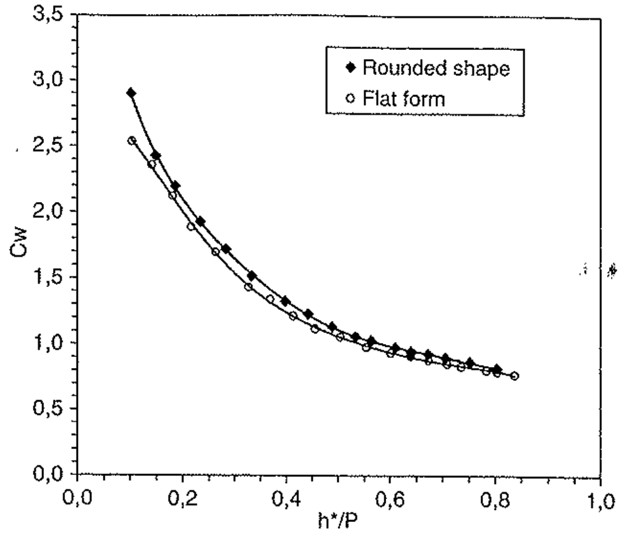

Figure 10. Coefficient of discharge according to the shape under the overhangs.

makes it possible to have a better efficiency. This is apparent for the relative heads $h^*/P < 0.5$. When the relative head is higher than 0.5 this advantage becomes weak. The figure 8 pointed out that for the same width of an element of P.K. Weir; it is possible at the same cost to increase the width of the upstream alveolus of 20% and to reduce consequently the width of the downstream alveolus. This increases efficiency about 5% without any additional expenditure. So it is more profitable to conceive the P.K. Weir with a width of the upstream alveolus larger than the width of the downstream alveolus.

4.5 *Impact of the overhangs length*

The impact of the overhangs length was studied according to three configurations, the first with overhangs upstream longer than the overhangs downstream ($c = B/3$, $d = B/6$, $d/c = 0.5$), the second configuration with overhangs upstream and downstream identical ($c = d = B/4$, $d/c = 1$) and the last configuration with only of the overhangs upstream ($c = B/2$, $d = 0$, $d/c = 0$). These three configurations were selected for reasons of structural design and construction in order to determine the most profitable solutions.

The Figure 9 shows that the model without downstream overhang ($d/c = 0$) is characterized by an efficiency higher than the models with downstream overhang. The increase of the capacity of the model with $d/c = 0$ is approximately 12% for relative head $h^*/P < 0.4$.

This result shows that the model without downstream overhang ($d/c = 0$) can be a solution for the great specific flows and the model with symmetrical overhangs represents an economic solution because of the symmetry of the overhangs, which favour the use of the prefabricated units.

4.6 *Impact of the shape of entry under the overhangs upstream*

The geometry of P.K. Weir makes that the weir becomes sensitive to the form of entry of the weir.

To check the impact of the shape of entry under the overhangs, two shapes of entry were considered, the first a flat form and the second correspond to a rounded entry shape.

Figure 10 shows that the design of a better hydraulic form to the vertical part under the overhangs upstream (as for the pillars of a gated weir), would increase the efficiency of P. K. Weir about 7% for a low additional cost.

4.7 *Impact of the floating debris*

In order to check the behavior of P.K. Weir in the case of operation in the presence of the floating debris, tests were carried out under conditions of extreme obstruction of the entry of the weir. During the experimentation, it was noticed that no blocking of the floating debris under the overhangs was observed during the rise of the water level from the base of P.K. Weir to the crest. For the low heads the floating debris are carried in the downstream alveoli and remain blocked until an average charge about 0.4 P. At this moment, the floating debris starts to be evacuated systematically towards the downstream.

Graph 12 shows that the impact of the floating debris is characterized by a reduction of the coefficient of discharge for relative heads $h^*/P < 0.5$, beyond this

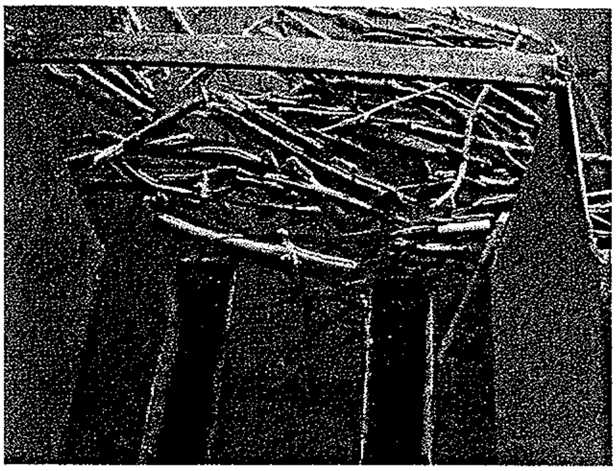

Figure 11. Operation of P.K.Weir with obstruction of the entry by floating debris.

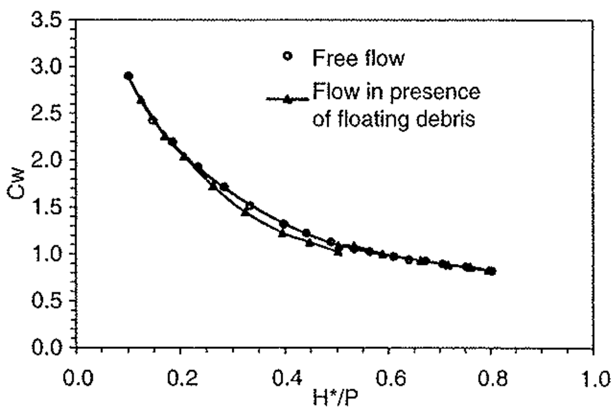

Figure 12. Coefficient of discharge according to the presence of the floating debris.

value, the flow becomes again normal and the coefficient of discharge takes values equal to the values corresponding to the free flow. The effect of the floating debris can reduce the flow about 10% when the depth of water on the weir is in the range of 1 or 2 m (As for the Creager weir).

This experimental analysis made it possible to select two types of P.K.Weir according to the hydraulic performance and the economic criterion. The first type of P.K.Weir (A) is characterized by overhangs upstream and downstream identical, this will favour the use of the prefabricated units out of reinforced concrete which can be used for specific flows up to 20 $m^3/s/m$ (Fig.13). The second type of P.K.Weir (B) is defined by overhangs only upstream, important profits in efficiency are about 10 % compared to type A are recorded. The structural efforts are less important for the great specific flows. That could thus be the choice the more attractive for several future dams (Fig.14).

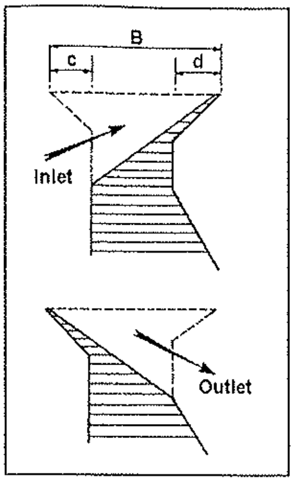

Figure 13. P.K.Weir (Type A).

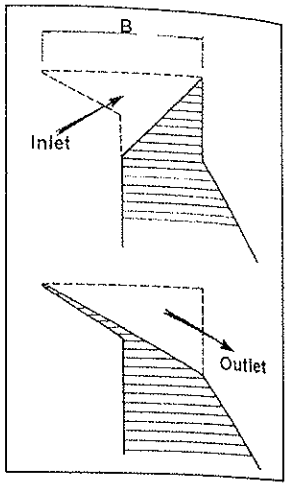

Figure 14. P.K.Weir (Type B).

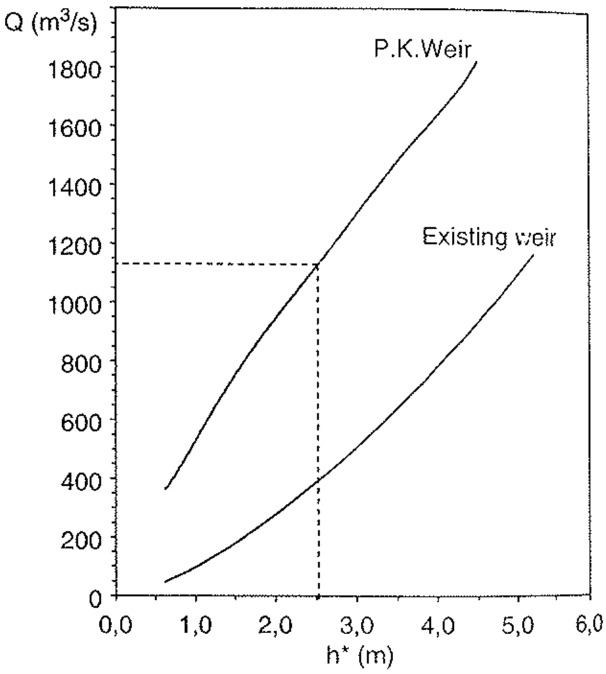

Figure 15. Discharge curve of the weir of the Zit Amba dam.

5 EXAMPLE OF APPLICATION OF THE P.K. WEIR FOR THE ALGERIAN DAMS

Two examples of application of P.K. Weir to real cases of dams were carried out. The first corresponds to the increase in the pool capacity of Zit Amba dam and the second example corresponds to the increase at the same time in the pool capacity and spillway capacity of Ain Zada dam.

5.1 *Zit Amba dam*

The Zit Amba dam is located at the department of Skikda in ALGERIA. This area is characterized by

Table 1. Geometrical characteristics of P.K.Weir.

P	B	W	a	b	c	d	Wt	n	L/W	W/P
m	m	m	m	m	m	m	m	/	/	/
5.7	17	4.54	2.27	2.27	5.68	5.68	50	11	8.5	0.8

the intensive development of industry and agriculture, which involves a considerable increase in consumption out of water. The building work of the dam was completed in November 2000.

The principal characteristics of the dam are: Average annual throughput: 50 Mm^3/an
Coast of the normal level of pool: 86
Coast of the maximum water level: 91
Coast of the dead level of pool: 62
Total capacity of pool: 120 Hm^3
Level of crest: 92
Height of the dam: 47.5 m
Length of the crest: 640 m
Width of crest: 10 m.

The spillway is established on right bank of the valley, it is designed to evacuate the maximum flood of 1094 m^3/s, under a head of water on the sill of the weir of 5 m. The weir is of type Creager high of 3 m, connected to a downstream convergent chute of 125 m length with a slope of the apron of 22,4%. The chute ends in a ski-jump. To compensate a part of the capacity of the pool lost following the silting, the solution of heightening of the sill of weir can be profitable. A heightening of the sill of 2.5 m will allow an increase of the pool capacity about 22 Mm^3 and will reduce consequently the load on the threshold of weir to 2.5 m. The choice of P.K. Weir for the heightening of the threshold can be a profitable solution. The specific flow being of 21.88 m^3/s, a P.K. Weir of type (A) with symmetrical overhangs will correspond to the most economic solution.

For a head of 2.5 m on the threshold of P.K. Weir the flow evacuated is of 1132 m^3/s. This solution will be led to a lowering of the existing sill about 3.2 m to allow the construction of P.K. Weir high of 5.7 m.

5.2 *Ain Zada dam*

The Ain Zada dam located in the department of Bordj Bou Arreridj (Algeria) is intended for the drinking water supply of the surrounding cities. It was built for the period 1981–1983. The principal characteristics of this dam are:

- Rockfill dam with a clay core.
- Capacity of pool 125 Mm^3 at the coast 855.
- Maximum water level (NPHE) 846.2, which corresponds to a capacity equal to 240 Mm^3.

Table 2. Geometrical characteristics of P.K.Weir.

P	B	W	a	b	c	d	Wt	n	L/W	W/P
m	m	m	m	m	m	m	m	/	/	/
9.0	18	7.2	3.6	3.6	9.0	0.0	75	10.4	6	0.8

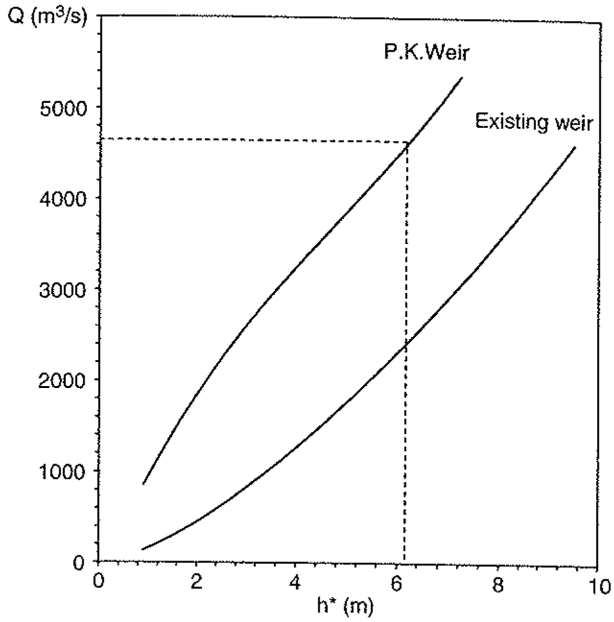

Figure 16. Head curve of the weir of the Ain Zada dam.

- Dead volume 15 Mm^3, at the coast 838.
- Width of the crest of the dam 7 m.
- Length of the crest 688 m.

The spillway is located remotely of dam on right bank of the dam in a natural ravine. It includes a weir of Creager type of 75 m of length, whose level of the threshold is at coast 855. The weir flows in a convergent rectangular chute long of 185 m, whose width passes from 75 m upstream to 45 m downstream. The chute of constant slope 8.4% makes 180 m of length and ends in a ski-jump. The spillway is designed to evacuate a flow of 4400 m^3/s under a water nappe of 9.2 m corresponding to crest 864.2. The Ain Zada dam is designed to satisfy the water requirement for the towns of Setif, Bordj Bou Arrerij and El Eulma to the horizon 2010. The increasing water requirements for the three Cities exceed the quantity of planned water. To make up for a part of the deficit, it is recommended to exploit the discharged volume of water which is estimated at 27 Mm^3/an. The exploitation of this volume requires the increase in the capacity of pool. The increase in the space of the reservoir can be obtained by the heightening of the threshold of the existing weir, while ensuring a degree of safety of evacuation of floods and to maintain the same maximum pool level. This choice appears to be profitable and feasible being given that the restoration is limited only to the weir. The heightening of the threshold of the weir of 3.0 m makes it possible to increase the capacity of the pool of 41 Mm^3 and reduces the head on the sill of the weir to 6.2 m, the maximum pool level being the same one as that before the heightening. The choice of P.K.Weir for the heightening appears to be an effective solution to increase at the same time the capacity of pool and the capacity of the weir. The specific flow being important (58.67 $m^3/s/m$), the most adequate solution corresponds to a P.K.Weir of the type B.

For a head of 6.2 m on the threshold of P.K.Weir the evacuated flow will be of 4650 m^3/s, that is to say an increase in the capacity of evacuation of 250 m^3/s. Consequently the threshold of the existing weir must be lowered of 6.0 m to allow the construction of P.K.Weir height 9.0 m.

6 CONCLUSIONS

The piano keys weir (P.K.Weir) represents an effective solution for the increase in the storage capacity and/or the capacity of evacuation of floods of the majority of the existing dams. It can be an economic solution for the new dams. This new type of weir is characterized by:

- A simple geometrical configuration which allows the use of prefabricated units.
- An operation similar to the weirs with free flow but much more effective.
- A specific flow of a standard weir multiplied by 2 to 4.
- It reduce considerably the cost of the majority of the new dams and guarantees their safety.
- It increase the storage of many existing reservoirs at a cost in the range of 0,05 $\$/m^3$ in most developing countries, under 0.5 $\$/m^3$ in industrialized countries.
- To improve the prevention of raw for much of existing dams.
- Increase the evacuation capacity for many existing dams with 0,5 m^3 of concrete reinforced by m^3/s additional.

Two examples of application of P. K. Weir for Algerian dams showed that this type of weir represents an effective solution to increase the storage capacity of pool.

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