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**DISCHARGE CAPACITY OF PK-WEIRS CONSIDERING
FLOATING WOODEN DEBRIS ¹**

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1. INTRODUCTION

A Piano Key weir (PKWs) is folded back and forth to create repeating keys similar to a Labyrinth weir (Fig. 1). This increases the discharge capacity of a PKW. The latter is several times higher than for a linear weir under a similar head, crest type and spillway width. As a result, the dam reservoir can be operated with a higher maximum operation level and the useful storage volume is increased. Alternatively, PKW serve to enhance the capacity of existing spillways, as for instance at Dartmouth Dam in Australia [1]. Combining a new PKW inlet on the spillway with an additional 3.4 m high parapet wall on the dam crest allowed to enhance the discharge capacity from 4'400 m³/s (with an ogee as inlet profile) up to 11'600 m³/s. In contrast to a Labyrinth weir, PKWs have up to 20% gain in discharge capacity and smaller footprints without extended base slab. Their installation on a narrow concrete dam crest is therefore possible.

Given that PKWs are relatively novel structures, only few design equations were proposed so far [2, 3, 4, 5]. Thus, physical model tests are often performed for verification of the hydraulic performance and for optimization of the structure

¹ *Débitance d'un déversoir en touches de piano considérant l'effet des corps flottants*

as a whole. Nevertheless, systematic research model test series were conducted in several laboratories in recent years. Based on such a test series conducted at EPFL, a general design equation for A-type PKWs is proposed and discussed hereafter. Furthermore, results of systematic tests with wooden floating debris and their effect on headwater raise are presented [6, 7].



Fig. 1

PKW at Malarce Dam in France

Déversoir en touches de piano du barrage de Malarce en France

2. RATING CURVE OF A PKW

The developed crest length L of a PKW is typically five to seven times its linear transversal width W . The flow is unaffected by the corners and edges of the PKW crest up to a head H similar to the wall thickness T_s – at least for cylindrical crests [8]. For such conditions, the PKW works hydraulically as a straight linear weir with a length being several times higher than the constructional inlet width. For higher heads, the corners and wedges start to reduce the discharge efficiency, but the latter remains significantly above that of a comparable linear weir or ogee. The standard PKW notation is applied hereafter according to Fig 2, with B = streamwise length, P = vertical height, and R = parapet wall height. The subscript i refers to the inlet key, i.e. the key filled with water for a reservoir surface at the crest, and subscript o to the outlet key, i.e. the dry key for the latter reservoir level. The developed crest length is $L=W+(2NB)$, with N as number of PKW cycles.

The main parameters having a significant effect on the PKW discharge capacity are L and H . The secondary parameters of small but not negligible effect include the ratio of inlet and outlet key widths, the ratio of inlet and outlet key heights, the relative overhang lengths, and the relative height of the parapet walls. Using PKWs with cylindrical crests and based on physical model tests, Leite Riberiro *et al.* [5] propose the rating curve computation as detailed hereafter. Note that their parameter variation – i.e. the application range of the proposed design equations – includes $3.0 \leq L/W \leq 7.0$, $0.1 \leq H/P_i \leq 2.8$, $1.5 \leq B/P_i \leq 4.6$, $0.7 \leq P_i/P_o \leq 1.4$, $0.2 \leq B_i/B = B_o/B \leq 0.4$, and $0.5 \leq W_i/W_o \leq 2.0$. To choose a hydraulically performing, constructional feasible, and economically shaped PKW, the recommendations of EDF may serve as basis [10], including $L/W=6$ to 7 , $P=4$ to 5 m, $W_i/W_o > 1.3$, and $T_s=0.35$ to 0.4 m. Further, downstream cavity aeration is recommended to avoid nappe vibrations.

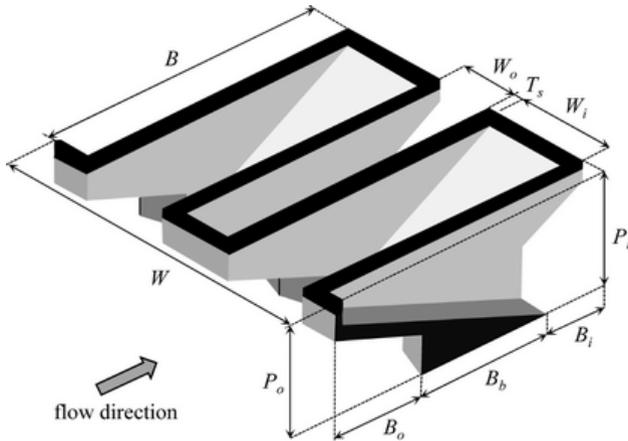


Fig. 2

Common PKW notation [9]

Notation standard pour un déversoir en touches de piano [9]

The PKW discharge Q_{PKW} is a function of $Q_S=C_S W(2gH^3)^{0.5}$, being the discharge over a linear sharp-crested reference weir with $C_S=0.42$ and a width W [5].

$$Q_{PKW} = rC_S W \sqrt{2gH^3} \tag{1}$$

The discharge enhancement ratio r , compared to the linear sharp-crested reference weir, is obtained as [5]

Q. 97 – R. 21

$$r = 1 + 0.24wpba \left(\frac{P_i(L-W)}{WH} \right)^{0.9} \quad [2]$$

The correction factors w , p , b , and a refer to the detailed geometrical specification of the PKW (Fig. 2). They include the ratio between inlet and outlet key width as [5]

$$w = \left(\frac{W_i}{W_o} \right)^{0.05} \quad [3]$$

the ratio between outlet and inlet key height as [5]

$$p = \left(\frac{P_o}{P_i} \right)^{0.25} \quad [4]$$

the ratio between key overhangs to the base length as [5]

$$b = \left(0.3 + \frac{B_o + B_i}{B} \right)^{-0.5} \quad [5]$$

And finally the relative parapet wall height as [5]

$$a = 1 + \left(\frac{R_o}{P_o} \right)^{2.0} \quad [6]$$

3. EFFECT OF WOODEN DEBRIS ON DISCHARGE CAPACITY

Debris is typically transported by a river during floods and can accumulate at hydraulic structures, e.g. at spillway inlets. There, it reduces the open flow area for water passage, resulting in a lowered discharge capacity combined with an increased flow depth in the upstream reservoir or channel. Such a level increase may affect the safety of the dam or the weir. The folded and complex geometry of

PKWs may be considered as prone for driftwood collection at first sight. The flow depth on a PKW for a given discharge is small, thus providing in principal less flow momentum per unit weir length for flushing driftwood.

Physical model tests conducted by Pfister *et al.* [6, 7] included three different PKW geometries as spillway inlets in reservoirs. A large variety of wooden debris including rootstocks was tested, combined with a systematic variation of unit discharges up to almost 13 m³/s. The specific drift wood volume arriving at the PKW reached almost 10 m³/m, defined relative to the weir width W . The main outcomes of the systematic model study are summarized for practical application as follows:

- the debris volume collected at a PKW increases with decreasing unit discharge,
- the driftwood volume trapped at the PKW increases with increasing driftwood volume arriving at the weir,
- the blockage density at a PKW is small due to a negligible approach flow velocity in the reservoir, so that the blocked driftwood volume remains permeable and superficial,
- single trunks tend to pass the PKW if their diameter is smaller than the critical flow depth, if no blocking is present before their arrival,
- the absolute head increase in the reservoir was, for the tested scenarios, always smaller than 0.2 m, and thus relatively small despite of the high debris volumes supplied combined with the small tested discharges, and
- the PKW discharge coefficient C_d decreases due to driftwood collection at the PKW. It is typically around 75% of the value without drift wood occurrence for specific discharges exceeding some 3 m²/s.

REFERENCES

- [1] PHILLIPS M.A., LESLEIGHTER E.J. (2013). Piano Key Weir spillway: Upgrade option for a major dam. Intl. Workshop *Labyrinth and Piano Key Weirs II* (PKW 2013), 159-168, CRC Press, Boca Raton.
- [2] KABIRI-SAMANI, A., JAVAHERI, A. (2012). Discharge coefficient for free and submerged flow over Piano Key weirs. *J. Hydraulic Res.*, 50(1), 114–120.
- [3] PFISTER, M., ERPICUM, S., MACHIELS, O., SCHLEISS, A.J., PIROTTON, M. (2012). Discussion of Discharge coefficient for free and submerged flow over Piano Key weir. *J. Hydraulic Res.*, 50(6), 642-643.
- [4] MACHIELS, O. (2012). Experimental study of the hydraulic behaviour of piano key weirs. PhD *Thesis*. HECE Research Unit, University of Liège B. <http://hdl.handle.net/2268/128006>.

- [5] LEITE RIBEIRO, M., PFISTER, M., SCHLEISS, A.J., BOILLAT, J.-L. (2012). Hydraulic design of A-type Piano Key weirs. *J. Hydraulic Res.*, 50(4), 400–408.
- [6] PFISTER, M., CAPOBIANCO, D., TULLIS, B., SCHLEISS, A.J. (2013). Debris blocking sensitivity of Piano Key weirs under reservoir type approach flow. *J. Hydraulic Engng.*, 139(11), 1134–1141.
- [7] PFISTER, M., SCHLEISS, A.J., TULLIS, B. (2013). Effect of driftwood on hydraulic head of Piano Key weirs. Intl. Workshop *Labyrinth and Piano Key Weirs II* (PKW 2013), 255-264, CRC Press, Boca Raton
- [8] PFISTER, M., BATTISACCO, E., DE CESARE, G., SCHLEISS, A.J. (2013). Scale effects related to the rating curve of cylindrically crested Piano Key weirs. Intl. Workshop *Labyrinth and Piano Key Weirs II* (PKW 2013), 73-82, CRC Press, Boca Raton.
- [9] PRALONG, J., VERMEULEN, J., BLANCHER, B., LAUGIER, F., ERPICUM, S., MACHIELS, O., PIROTTON, M., BOILLAT, J.L., LEITE RIBEIRO, M., SCHLEISS, A.J. (2011). A naming convention for the Piano Key weirs geometrical parameters. Intl. Workshop *Labyrinth and Piano Key Weirs*, 271-278. CRC Press, Boca Raton.
- [10] LAUGIER, F., VERMEULEN, J., LEFEBVRE, V. (2013). Overview of Piano Key Weirs experience at EDP during the past few years. Intl. Workshop *Labyrinth and Piano Key Weirs II* (PKW 2013), 213-226, CRC Press, Boca Raton.

SUMMARY

Piano Key weirs are applied because of their highly efficient discharge capacity, combined with a small footprint, low construction costs as well as construction times. Several PKW are successfully in operation or under construction. They mainly serve to enhance the discharge capacity of an existing spillway. Based on systematic hydraulic model tests, empirical design equations were developed, considering the involved geometrical parameters. Further, the PKW sensitivity regarding the impact of blocked driftwood was studied. The latter is relatively small, with a maximum upstream water level increase of only 0.2 m. This is probably due to: (1) the blockage density remains loose with a high permeability because of the small approach flow velocities, and (2) a major flow part passes underneath the blockage into the inlet key, not being affected by the floating blocking occurring mainly near the upstream crest of the outlet key.

RÉSUMÉ

L'utilisation des déversoirs en touches de piano (PKW) est intéressante à cause d'une haute débitance combinée avec une petite empreinte de la

fondation, ainsi que de faibles coûts de construction et une courte durée de réalisation. Plusieurs PKW sont déjà en exploitation avec succès ou en construction, avec comme objectif principal d'augmenter la capacité des évacuateurs de crues existants. Basées sur des essais systématiques sur des modèles réduits, des relations empiriques pour le dimensionnement hydraulique des PKW ont été développées en considérant les paramètres géométriques. En plus, l'importance des corps flottants a été étudiée. Avec l'observation d'une augmentation maximale du niveau d'eau amont de 0,2 m, l'importance des bois flottants reste relativement modérée. Ceci est probablement expliqué par les raisons suivantes : (1) la densité des tas de bois bloqués reste relativement faible avec une grande perméabilité à cause des vitesses d'approche modérées, et (2) une grande partie du débit peut passer en-dessous des tas de bois dans les alvéoles aval qui ne sont pas affectées par les accumulations de bois, puisque celles-ci se forment surtout aux alvéoles amont.