Large scale experimental study of piano key weirs

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ABSTRACT

Piano Key Weirs (PKW) are a new type of weir, showing very good flood release capacities as well as strong economic and structural benefits. However, lacks of understanding persist about the flow conditions on such structures. With the goal to fill some of these lacks, a combined experimental and numerical study has been undertaken at the Laboratory of Structures Hydraulics of the University of Liege.

This paper presents the goals and the scientific strategy of this research. The first results of experiments being carried out on a large physical model of PKW are also depicted. These experiments lead to characterization of the flow behavior for low heads and enable to highlight the influence of the crest thickness and the outlet slope on the release capacity.

1. INTRODUCTION

The interest of piano key weirs (PKW) to increase the performance of existing spillways or to design more efficient new dams is no more to demonstrate. Indeed, 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 (Lempérière 2003).

Several studies have been carried out in different laboratories to characterize the influence of some geometrical parameters on the discharge capacity of the PKW (Chi Hien 2006, Lempérière 2006, Machiels 2009). Indeed, the PKW, looking like modified labyrinth weir, shows geometric specificities such as up- and/or downstream overhangs, inlets and outlets bottom slopes, which induce a large set of variable parameters (Figure 1).

The main geometric parameters of a PKW are the transversal weir width W, the weir height P, the number of PKW elements n (number of inlets and outlets), the lateral crest length B, the inlet and outlet widths a and b, the up- and downstream overhang lengths c and d and the wall thickness t (Lempérière 2006).



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

On another hand, the first real size PKW has been built by EDF in France during summer 2006 to increase the discharge capacity of the Goulours dam spillway (Laugier 2007). With the experience issued from this first realization and the results of other experiments carried out in several laboratories, EDF developed the use of PKW for the rehabilitation of different dam spillways in France. The second PKW has been built on the St Marc dam during summer 2008 and the third one will be built during summer 2009 on the Gloriettes dam (Bieri 2009).

Till now, the hydraulic design of a PKW is still performed on the basis of experimental knowledge and scale model studies, modifying step by step an initial geometry following the ideas of the project engineers (Ribeiro 2006).

Today, there is thus a strong need for fundamental as well as applied studies on PKW to improve the understanding of the flow behavior on this new type of weir and to set up efficient design rules to predict its discharge capacities. These are the reasons why a combined experimental and numerical study of PKW is undertaken at the Laboratory of Structures Hydraulics of the University of Liege.

2. PRESENTATION OF THE STUDY

2.1. Goals and scientific strategy. The first goal of the 4-year study presented in this paper is to enhance the understanding of the physics of the flows on a PKW to clearly define the interests and limitations of this type of weir. This will be achieved by the exploitation of a large experimental model of PKW in a wide range of discharges.

In a second time, the study aims to allow determining the influence of the different geometrical parameters of the PKW on its discharge capacity. To achieve this goal, several scale models with variable geometries will be tested. In parallel to these experimental tests, numerical modeling will be performed to improve existing flow solvers at University of Liege and to help in defining the most important geometrical parameters of the weir.

Finally, the study will seek to define analytical formulations of the discharge coefficient of PKW to be used during the design stage of new structures.

2.2. Experimental facility. A specific experimental facility has been built to perform the scale model tests depicted in paragraph 2.1. A channel, 7.2 m long, 1.2 m wide and 1.2 m high has been built in the Laboratory of Structures Hydraulics at the University of Liege (Figure 2 and 3).



Figure 2. Experimental channel layout (Dimensions in cm)



Figure 3. Experimental channel

The channel is fed by two pumps delivering up to 300 l/s in an upstream stilling basin. The upstream entry of the channel is equipped with a metal grid and a synthetic membrane ensuring uniform alimentation conditions.

Two Plexiglas plates on both channel sides allow to observe the flow patterns on the whole channel height at the location of the PKW model. Specific convergent structures allow to reduce the channel width to the variable width of the tested models.

2.3. Large scale model. The first experiments have been carried out on a large scale model of a basic PKW geometry (Figure 4) to define precisely the transitions between the different flow types on the weir crests and to characterize these different flow types in terms of velocity, pressures and flow patterns.

To achieve this goal, 1.5 inlets and 1.5 outlets have been modeled. Thus, half an outlet and half an inlet are along the Plexiglas wall while the full alveolus are at the center of the channel, without side effects.



Figure 4. Large scale model layout (Dimensions in cm)

Discharge and upstream head measurements are performed respectively with an electromagnetic flowmeter and a limnimeter with a precision of ± 1 l/s and ± 0.5 mm. Dyes are used to identify different flow behaviors depending on upstream head variation. Specific instrumentation of the model with water level, velocity and pressure transducers is planned.

3. PRESENTATION OF THE FIRST RESULTS

3.1. Release capacity. Because of the complexity of the PKW geometry, the discharge capacity is a function of many geometric parameters. It is thus of common use to express the discharge Q on a PKW under a water head H regarding the weir length W on the dam crest:

$$Q = C_w W \sqrt{2gH^3}$$

All the weir geometric specificities are thus contained in the discharge coefficient C_w (Lempérière 2006).

The following $C_w / H/P$ curve can be drawn regarding the first experiments results (Figure 5). The black lines show the influence of the discharge measure accuracy on the C_w values.



Figure 5. Non-dimensional head / discharge coefficient curve of the model

This curve is relatively close to the curves presented by Lempérière (2006) for non-optimal characteristics of PKW. Indeed, the geometry of the model has been defined to emphasize the differences between various flow types on the weir by increasing the slopes of both inlets and outlets, what globally decreases the PKW efficiency.

However, for low water heads (H/P < 0.15), there is an important decrease in the discharge coefficient compared to the Lempérière's results. The explanation of this phenomenon is the influence of the crest thickness *t* and shape. Indeed, the Lempérière's experiments have been carried out on a model with a negligible wall thickness (steel plates), whereas the model presented in this paper has a walls thickness of 2 cm on the lateral crest and 2.5 cm on the upstream and downstream crests (use of 2 cm thick PVC plates).

These dimensions are in agreement with the usual concrete thickness of PKW walls. However, the shape of the crests on the scale model is flat and has thus not been profiled at this stage of the study.

3.2. Low heads behavior. The large scale of the model together with the transparent walls enables to precisely observe the flow behavior over the weir crests. For low water heads, the importance of the wall thickness has already been underlined. The transition from a partially clinging nappe to a depressed nappe and then to a free nappe can be observed on the different parts of the PKW crest. These transitions occur for different heads depending on the crest (lateral, downstream or upstream).

On the lateral crests, for the smallest head ratio (H/P = 0.05), the depressed nappe remains in contact with the crest. For head ratios H/P between 0.09 and 0.1, what corresponds to ratios H/t of 2.35 to 2.6, the nappe becomes free and is detached from the crest on the most downstream 3/4 of the crest length (Figure 6). This situation persists for higher water heads.



Figure 6. Transition from a depressed to a free nappe on the lateral crest

The same behavior is observed on the downstream crest of the inlet. The transition from a depressed to a free nappe is observed for head ratios H/P between 0.11 and 0.12, what corresponds to ratios H/t between 2.4 and 2.6 (Figure 7). The inlet slope has thus no effects on the nappe shape for low heads.



Figure 7. Transition from a depressed to a free nappe on the downstream crest

The flow behavior on the upstream crest is different. Indeed, for the lowest head ratios, the nappe is completely attached to the walls. Then for head ratios H/P between 0.16 and 0.17, i.e. ratios H/t between 3.48 and 3.64, the nappe is directly fully aerated (Figure 8). The downstream slope of the outlet has thus an important effect on the nappe shape.



Figure 8. Transition from a clinging to a free nappe on the upstream crest

Schoder and Turner (1929), cited by Lakshmana Rao (1975), studied the variations of the discharge coefficient with the nappe shapes at very low heads on sharp crested weirs, i.e. the same case as in the scale model.

Their results are summarized in the table of Figure 9, where (a) and (b) denote free nappes, (c) denotes depressed nappes, and (d) and (e) denote respectively partially and fully clinging nappes.



Figure 9. Variation of discharge coefficient at low heads (sharp crested weirs) (Lakshmana Rao 1975)

The same correlation has been found on the PKW scale model (Figure 10). The discharge coefficient grows with the head for very low heads where nappe is depressed all over the weir crest (Figure 10 - a). Then, when the nappe becomes free on the 3/4 of the lateral crest length, the discharge coefficient decreases with the head before increasing again (Figure 10 - b). That can be explained by the opposite effects of the free nappe on the lateral crest, which decreases the discharge coefficient, and of the depressed nappe on the downstream crest and the clinging nappe on the upstream crest, which increases the discharge coefficient. When the downstream nappe becomes free, the same phenomenon can be observed with a more important decrease and a less important increase because of the combined action of the lateral and downstream nappes against the upstream one (Figure 10 - c). Finally, the discharge coefficient decreases constantly when the upstream nappe is free (Figure 10 - d).



Figure 10. Variation of the discharge coefficient at low heads on the PKW model

4. CONCLUSIONS

In order to improve the understading of the flows over PKWs, an experimental study is undertaken at the University of Liege. A large scale model has already been built and exploited to characterize the different flow types on the weir crests. This experimental program will be completed by numerical modeling.

The first experimental results enable to highlight the influence of the crest thickness on the nappe shape and the weir discharge capacity for low heads, consistently with previous published results correlating the discharge capacity and the nappe shape on sharp crested weirs.

REFERENCES

- Bieri, M., Ribeiro, M. L., Boillat, J.-L., Schleiss, A., Laugier, F., Delorme, F., and Villard, J.-F. (2009). "Réhabilitation de la capacité d'évacuation des crues – Intégration de "PK-Weirs" sur des barrages existants." *Colloque CFBR-SHF*, Paris.
- Chi Hien, T., Thanh Son, H., and Ho Ta Khanh, M. (2006). "Results of some "piano keys" weir hydraulic model tests in Vietnam." *CIGB/ICOLD*, Barcelona.
- Lakshmana Rao, N. S. (1975). "Theory of weirs." In: Chow, V. T. (ed.). "Advances in Hydroscience" vol. 10, Academic Press.
- Laugier, F. (2007). "Design and construction of the first Piano Key Weir (PKW) spillway at the Goulours dam." *Hydropower & Dams*, Issue 5.
- Lempérière, F., and Ouamane, A. (2003). "The piano keys weir: a new cost-effective solution for spillways." *Hydropower & Dams*, Issue 5.
- Lempérière, F., and Ouamane, A. (2006). "Design of a new economic shape of weir." *The International Symposium on Dams in the Societies of the 21st Century,* Barcelona.
- Machiels, O., Erpicum, S., Archambeau, P., Dewals, B. J., and Pirotton, M. (2009).
 "Analyse expérimentale du fonctionnement hydraulique des déversoirs en touches de piano." *Colloque CFBR-SHF*, Paris.
- Ribeiro, M. L., Boillat, J.-L., Schleiss, A. J., Laugier, F., and Albalat, C. (2007).
 "Rehabilitation of St-Marc dam. Experimental optimization of a piano key weir." *Proceedings of the 32nd Congress of IAHR*, Venice.