Hydraulic modelling of Piano Key Weirs: a composite approach

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Abstract:
During the last few years, several piano key weirs (PKWs) have been built in France and abroad. Thanks to the reduced footprint and high release capacities of this new type of weir, making it particularly suited for concrete dams rehabilitation, lots of other projects in various countries are under construction or study. The prototype use of PKW requires knowledge about its structural behaviour, hydraulic capacities as well as integration into dams' environment. This paper aims at presenting numerical and physical modelling works performed at the University of Liege to address the last two items. In particular, large scale physical modelling and parametric scale models have enabled to understand the hydraulic behaviour of the structure and to highlight its most influencing geometric parameters as well as their best variation interval depending on various criteria related to the weir design (discharge efficiency, cost…). A 1D numerical model has also been developed based on these experimental investigations. It enables to predict in a few minutes, with 10% accuracy, the discharge capacity of a given PKW geometry within its usual range of operation head. This model, available as a freeware from http://www.pk-weirs.ulg.ac.be, constitutes a key tool for the first design of such weirs. Finally, the scale model studies of major projects such as Raviège dam (France) for Electricité de France - EDF and Ouldjet Mellegue Project (Algeria) for Coyne et Bellier – Tractebel Engineering enable to confront theoretical predictions with experimental results and to address the problem of PKW integration on dam crests.

Key words: numerical modelling, physical modelling, parametric study, scale model

1. Introduction:

In hydraulic engineering, physical modelling has always been widely used for research as well as project design. This modelling approach consists in building, with a degree of complexity dependent on the goals of the application, a model of the hydraulic systems to be studied (ASCE, 2000). It enables to reproduce, in a controlled environment making a qualitative as well as quantitative analysis possible, the whole complexity of the flows occurring in the studied systems. Numerical modelling is nowadays another powerful tool to solve many of hydraulic engineering problems and to predict with accuracy flow patterns on a large set of hydraulic structures. It has been developed following the setup of increasingly representative mathematical models as well as more and more robust and accurate resolution schemes, coupled to a tremendous increase and popularization of computational power. Such an approach is currently widely used by engineers all over the world. Indeed, numerical models have low application costs compared to physical models, are flexible and enable easy results analysis.

Today, the combined application of physical and numerical modelling techniques, called composite modelling, is obviously the most effective response to most flow problems analyses. It enables combining the inherent advantages of both approaches, which are complementary, while being beneficial to the delays as well as the quality of the analysis (Erpicum et al., 2012a).

This paper aims at summarizing the results of the application at the University of Liege, during the last four years, of physical and numerical hydraulic modelling techniques to the study of hydraulic problems related to piano key weirs (PKWs). In particular, preliminary large scale physical modelling enables to understand the hydraulic behaviour of the structure and to highlight its most influencing geometric parameters (section 2). A 1D numerical model has been developed based on these experimental investigations to quickly predict the discharge capacity of a given PKW geometry within its usual range of operation head (section 3). This numerical model has also been used to define the best variation interval of the parameters identified by the large scale model study depending on various criteria related to the weir design. Finally, parametric physical experiments have been carried out to confirm and optimize the numerical results (section 4). In addition to valuable insights into optimal geometric ratios, the parametric tests have enabled to set up and validate an analytical formulation for the PKW head/discharge relation.

In parallel, scale model studies of major real projects in France and Algeria have enabled to confront theoretical predictions with experimental results and to address the problem of PKW integration on dam crests (section 5).

2. Large scale experimental modelling:

To enhance the understanding of the flow over a PKW, a large experimental model has been built and exploited on a wide range of discharges (Machiels et al, 2011a). The model represents, with a scale factor around 1:10, a simplified sketch of a PKW made of 1.5 inlets and 1.5 outlets. Such a sketch has been shown to be relevant to study the flow over a full PKW (Le Doucen et al., 2009). In the test flume, the half inlet and half outlet were placed along the Plexiglas walls to enable the flow visualization while the full alveoli were located along the centreline of the flume, not submitted to side wall effects. The tests have provided dense data about the release efficiency of a PKW. They have also enabled to define the transitions between different flow types on the weir crests (outlet, lateral and inlet) and to characterize the flow on the structure in terms of velocities, pressures, free surface levels and flow patterns (Machiels et al, 2011a).

This study showed the important influence of the crest shape on low head operation. It also demonstrated that, whatever the head ratio, the pressure profiles are generally close to hydrostatic everywhere in the inlet. More importantly, for increasing heads, a control section moves towards upstream from the downstream crest of the inlet. This control section induces an evolution of the free surface profile along the inlet from a flat to a rippled one (Fig. 1). It reduces the weir efficiency as it limits the discharge released on the downstream part of the weir, which is no more related to the whole developed crest length. This last observation enables to explain the interest previously identified to increase the inlet width, the inlet slope or the inlet height. Indeed, these parameters directly influence the inlet cross section area, and thus the maximum head ratio before occurrence of the control section.

The conclusions of the large scale model study showed that three non dimensional parameters are particularly important regarding the PKW hydraulic capacity. Consistently with the nomenclature proposed by Pralong et al. (2011a) (Fig. 2), they are the key widths ratio W_i/W_o, the key slopes $P_i/(B-B_o)$ and $P_o/(B-B_i)$ and the overhangs relative position. In order to decrease the time of the physical investigations, a pertinent range of variation has been defined for each parameter using numerical modelling (see section 3).

3. Numerical modelling:

3.1 Complementary approaches:

Various numerical hydraulic models have been developed to date in hydraulic engineering, ranging from non-spatially distributed models (e.g. Dewals et al., 2011) to full 3D flow solvers. Regarding PKWs, two families of models have been applied so far.

3D modelling of the flow over a PKW has been performed by Electricité de France (EDF) using the commercial software Flow3D®. EDF carries out in such a way parametric studies as well as preliminary design of real PKWs projects (Vermeulen et al., 2011). Successful validation regarding experimental data has been achieved. Mean relative deviation in specific flowrates lower than 5% has been obtained considering various physical models geometries. Typical modelling considers neighbouring half an inlet and half an outlet, discretized with 1 million of cells, and reaches a steady state solution within an 8 hours calculation time on an eight 2.5 GHz cores computer (Pralong et al., 2011b). The level of details of the numerical results enables deep analysis of the flow characteristics everywhere on the structure.

On another hand, a 1D model has been developed at the University of Liege, aiming at rapidly providing a good evaluation of the hydraulic efficiency for a given PKW geometry (Erpicum et al., 2010 & 2011b). This simple to apply and little time consuming solver, available as a freeware from http://www.pk-weirs.ulg.ac.be, is depicted in the next sub-section.

3.2 Freeware WOLF1D-PKW:

The freeware WOLF1D-PKW has been developed by the HECE research group of the University of Liege, on the basis of the conclusions of the large scale physical tests depicted in section 2. For a given PKW geometry, it computes the flow over half a unit of the weir for a given range of discharge upstream of the structure. The results of the computation are the water level upstream of the weir depending on the discharge and the distribution of water depth and discharge along both the inlet and the outlet.

The numerical model considers the smallest hydraulic element of a PKW, made of a lateral wall, half an inlet and half an outlet. The inlet and the outlet are modelled as parallel 1D channels, possibly interacting by exchanges of mass and momentum along the lateral crest, and linked by a common upstream reservoir.

Comparison of the numerical results with experimental data for various geometries and from different Laboratories (Laboratoire National d'Hydraulique et Environnement – EDF, Chatou, France; Hydraulic Department of Biskra University, Biskra, Algeria and Laboratoire d'Hydraulique des Constructions - ULg, Liege, Belgium) showed an accuracy better than 10% on weir hydraulic efficiency for a wide range of upstream head (Fig. 3).

More details about the mathematical model, the numerical scheme and the modelling assumptions can be found in dedicated papers (Erpicum et al., 2010 & 2011b), together with additional validation examples.

In the scope of the study depicted in this paper, prior to a parametric scale model study, the numerical model has been used to define the best variation interval of the parameters identified by the large scale model study depending on various criteria related to the weir design.

4. Parametric scale model study:

A parametric scale model study of the geometric parameters has been performed using scale models to confirm and optimize the numerical results.

The results of experiments led on models with varied key widths ratio W_i/W_o, keeping the unit width W_u constant (Machiels et al., 2012b), showed that W_i/W_o ratios between 1.25 and 1.5 provide hydraulically optimal geometries whatever the weir height, for usual values of the design head. However, technico-economical reasons may justify the use of constant key widths combined with a low PKW height, which may facilitate the use of precast elements. This economic geometry involves loss of efficiency around 30% compared with the hydraulic optimum, but of less than 2% compared with a PKW of same height but optimized W_i/W_o ratio. Regarding the inlet slope, which is defined as the ratio between the weir height P_i and the length $(B\text{-}B_o)$, the hydraulic optimum is close to or higher than 1. Parapet walls, which are sometimes used to increase the weir height P at constant inlet bottom slope S_i, increase the PKW efficiency only if they increase the $P_i/(B\text{-}B_o)$ ratio closer to its optimal value (Machiels et al., 2012a). Finally, optimal overhangs relative position is closely related either to the inlet slope and width (downstream overhang) or to the outlet ones (upstream overhang). Indeed, the inlet key has to convey enough water to feed the whole downstream overhang length while the outlet key has to be able to release all the discharge from the upstream one.

In addition to these valuable insights into optimal geometric ratios, the parametric tests enable to set up and validate an analytical formulation for the PKW head/discharge relation (Machiels et al., 2011b).

5. Real project scale models:

Hydraulics of real PKW projects is usually studied on scale models (Leite Ribeiro et al., 2007; Laugier, 2007; Laugier et al., 2009). Such an approach is useful to verify the structures design but also to analyse related problems such as flow patterns in the reservoir, energy dissipation or interaction with other structures.

The following paragraphs illustrate these words in the case of the upgrade of an existing dam in France and a new dam project in Algeria, both considering a PKW as spillway solution.

5.1 The Raviège Dam (France):

The Raviège dam, operated by EDF, is located on the Agout River, near the town of Toulouse, in South West of France. It is a concrete buttress 40-m high dam, built in 1957 for electricity production. The release capacity of the two existing gated spillways, located in the centre of the dam, is 1,000 m³/s under the reservoir Maximum Water Level (MWL). Recent update of the hydrology calculations of the dam catchment area revealed new estimations of extreme floods far higher than those considered at the dam design stage (increase by 72%).

Most of the solutions to face safely the new extreme floods combine the use of the reservoir storage capacity and an additional spillway on top of the dam, on the left side of the existing gates. Following technico-economical studies including safety considerations, the new spillway has been designed as a free overflow. A PKW configuration has been chosen by the Dam Owner.

The PKW has a height P_i of 4.22 m and a global width W of 25.82 m. Its crest is at the reservoir Normal Water Level. It counts for 5 inlet and 5 outlet keys framed by a specific inlet key on the right side and a specific outlet key on the left side. It has a 1 m high parapet on the outlets apex and a constant bottom slope in the inlets. The weir length B is 13.24 m with 3.96 m long upstream overhangs and 3.45 m long downstream ones. The weir developed length L is 176.6 m. The lateral walls thickness T_s varies from 35 cm to 25 cm and decreases with the altitude in order to reduce the useless materials quantities and thus increase as much as possible the keys section. At the crest level, the inlet keys width W_i is 2.35 m and the outlet keys width W_o is 1.60 m. The outlet nose has a triangular shape. A concrete beam has been added upstream of the PKW to guarantee its stability on its own. Indeed, because the dam is affected by moderate concrete blowing pathology, the PKW will not be anchored to the existing structures. More details may be found in Erpicum et al. (2012b).

A hydraulic scale model has been used to determine the PKW features, to validate its integration within the existing structures and to design the downstream works. The scale model study has been realized considering the Froude similitude, with a 1/35 geometric scale factor. The model represents the whole dam structures, a 150-m long reach of the natural river downstream and a 230 x 210 m² area in the reservoir.

Experimental tests enable to determine the discharge capacity of the PKW and show the very limited influence of the existing and projected spillways on their respective discharge capacity. Considering a Creager weir of same width on the dam crest, the Raviège dam PKW is 3 times more efficient at the reservoir MWL (Fig. 4). Regarding the results of Lempérière et al. (2003) for the same type of PKW, the Raviège dam PKW is a little bit more effective in its relevant range of head, i.e. lower than 1.5 m (reservoir level lower than MWL).

Special care has been devoted to the study and design of the structures downstream of the PKW. Indeed, the new weir is located on the left side of the dam and the flow coming out of the weir needs to be deviated to the right, towards the main river bed, to avoid damage to the left bank of the valley. The main difficulty of the design lies in the relatively small energy of the flow coming out of the PKW combined to the reduced length of the spillway channel. This made hard the concentration of the flow and its deviation using a flip bucket or convergent walls. The energy dissipation structure has been designed as a converging smooth channel with varied slopes and downstream deflectors. The final design consists in, from right to left, a 8.75 m wide sky jump, an intermediate inclined flat apron and a three sections side wall perpendicular to the spillway channel, reducing progressively its width (Fig. 5 - right). This structure enables to concentrate the strongly aerated flows coming out of the PKW and to turn them towards the main river bed, at a place where the flow released through the gated spillways induces a thick water cushion (Fig. 5 - left).

5.2 Ouldjet Mellegue Project (Algeria):

The Ouldjet Mellegue Project in Algeria concerns the building of a RCC dam equipped with a PKW. Requested flood release capacities and dam site geometry constraints lead to design a PKW (Fig. 6) made of 12 outlet and 11 inlet keys. The outlet keys width W_o is 3.2 m and the inlet keys width W_i is 4.4 or 5.4 m, one inlet key out of two having at the centre a 1 m wide pier. Lateral walls thickness T_s is 40 cm. The total width of the PKW on the dam crest W is 97.8 m. The PKW height at inlet P_i is 6.8 m, the length of the upstream overhang B_o is 2.85 m and the one of the downstream overhang B_i is 3.18 m. The length of the keys B is 16.2 m for a base length of the structure B_b equal to 10.17 m. The bottom slope is 28.32° in the outlet keys and 27.7° in the inlet keys. Steps have been designed in the outlet keys, such as suggested by Leite Ribeiro et al. (2007). The outlet upstream face is not profiled and there is no parapet wall on the weir crest, which is horizontal. A 1.8 m wide specific outlet key at each of the weir extremities enables to simplify the design of the side walls at the weir entrance and to limit the height of the lateral walls in the spillway channel. The developed length of the PKW L is 451.1 m.

Discharge coefficient related to the weir width on the dam crest ranging from 1.85 for upstream head ratio H/P equal to 0.1 to 0.8 for H/P ratio equal to 0.7 are provided by this geometry. The maximum discharge is 3,330 m^3/s under a 4.5 m head; maximum specific discharge is 34 m^2/s in the spillway.

In this project, the PKW is projected upstream of a stepped spillway and a downstream stilling basin. Indeed, PKW geometric features create interacting flows and jets downstream and thus energy dissipation and air entrainment. These observations suggest that the use of a PKW to control the flow upstream of a stepped spillway may help in enhancing energy dissipation on the downstream channel. In order to verify this assumption and to validate the spillway project geometry, two scale models studies have been carried out.

An existing facility at the HECE laboratory has been used to compare, in an idealized environment, the energy dissipation on a stepped spillway downstream of a PKW with the one which takes place on the same spillway equipped with a standard ogee-crested weir. Two varied layouts of PKW, similar to the Ouldjet Mellegue Project one, have been considered upstream of the stepped spillway. The first PKW (PKW 1) represents 1.5 inlets and 1.5 outlets while the second one (PKW 2) is made of 2.5 inlets and 2.5 outlets. PKW 2 dimensions are generally 1.6 times smaller than PKW 1 ones, except the global width, which is the one of the experimental facility and the walls thickness which have to match the dimensions of commercially available plastic plates. The scale factor of PKW 1 regarding the Ouldjet Mellegue Project prototype is 1/26. It is 1/42 for PKW 2.

In the above mentioned geometric context, experimental tests revealed that the energy dissipation along the spillway is equivalent if the structure is equipped with an ogee-crested weir or two different layouts of a PKW. This can be explained by the structure length which is certainly sufficient to reach near uniform flow conditions at the spillway toe in the range of discharges considered (Erpicum et al., 2011a). Although additional tests with smaller spillway length are still under progress, important differences in the flow have been observed depending on the type of weir at constant discharges. With PKW models, the flow is fully aerated at the beginning of the spillway, whatever the discharge. This is not the case with the ogee crested weir (Fig. 7). These observations are consistent with these of Ho Ta Khanh et al. (2011). They suggest quicker effective energy dissipation downstream of a PKW than downstream of an ogee-crested weir, thanks to the rapid development of skimming flow conditions.

In a second time, a general scale model of the dam and spillway structures has been built using the Froude similarity and a 1/50 geometric scale factor. In addition to the weir, the spillway channel and the stilling basin, the scale model represented a 300 m long reach of the natural river downstream and a sufficient area of the reservoir to avoid an effect of the boundary conditions on the flow over the weir. This general model has enabled to validate the general layout of the spillway, to determine the release capacity of the PKW, to optimize the design of the spillway channel and the stilling basin and to measure the characteristics of the flows released in the downstream natural river for discharges up to the 10 000-year flood.

6. Conclusions:

In order to improve the understanding of the flows over a PKW, several research projects have been or are currently undertaken at the University of Liege and abroad, using complementary experimental and numerical modelling approaches and various scales of analysis.

All these studies underline the high efficiency of the PKW in terms of discharge capacity, especially for low heads, and thus its efficiency regarding dams' safety and floods management.

The research works presented in this paper will be pursued, aiming at defining practical formulations to be used for the hydraulic design of PKW, as well as at investigating other related problems such as energy dissipation.

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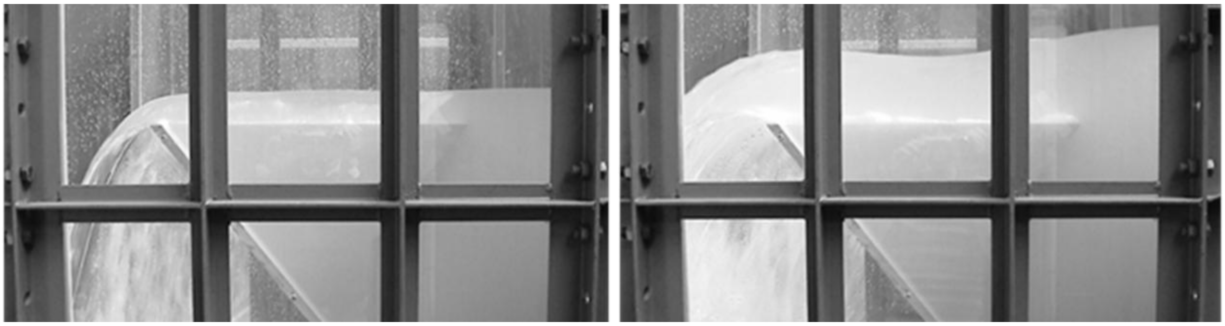

Figure 1: Large scale model of a PKW - Transition from a flat (left) to a rippled (right) free surface profile with increasing head

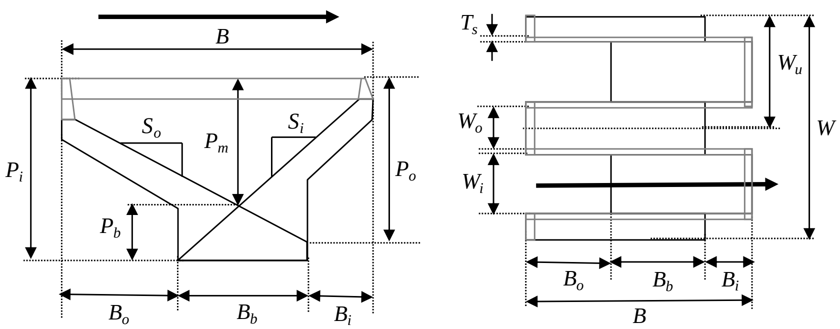

Figure 2: Geometric parameters of a PKW – Typical cross section (left) and plan view (right) (Pralong et al., 2011a)

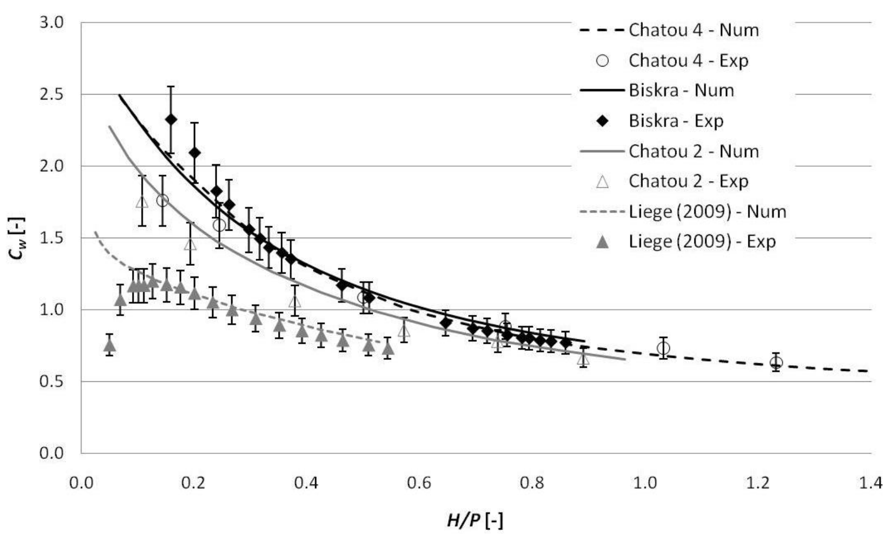

Figure 3: Comparison between experimental and numerical non-dimensional heads H/P versus discharge coefficient C_w curves for physical models from Chatou (France), Biskra (Algeria) and Liege (Belgium). ±10% variation bars on the experimental discharge coefficients.

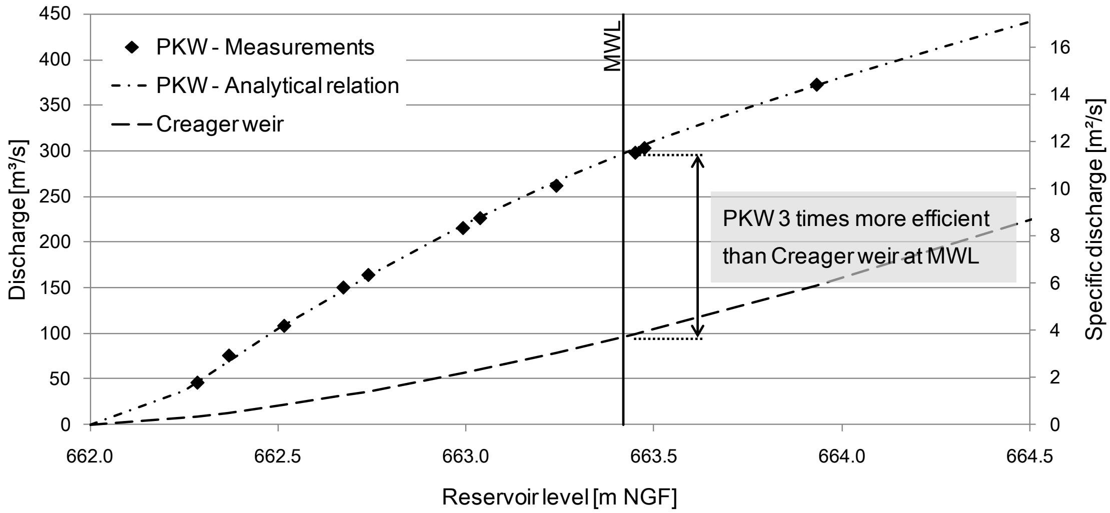

Figure 4: Raviège Dam upgrade - Head / discharge curve of the PKW and comparison with a Creager weir of same width on the dam crest

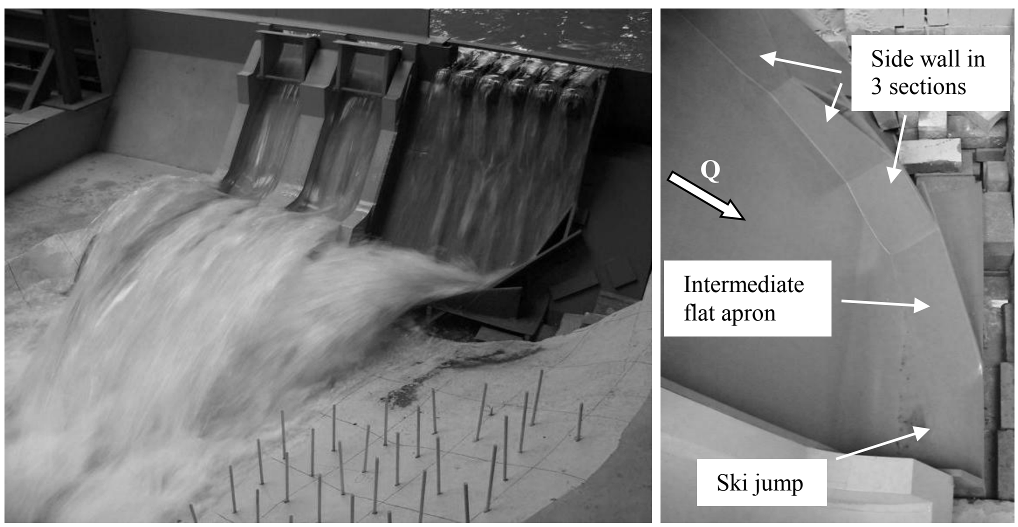

Figure 5: Raviège Dam upgrade - Peak discharge of the design flood on the scale model (left) and details of the downstream structure (right)

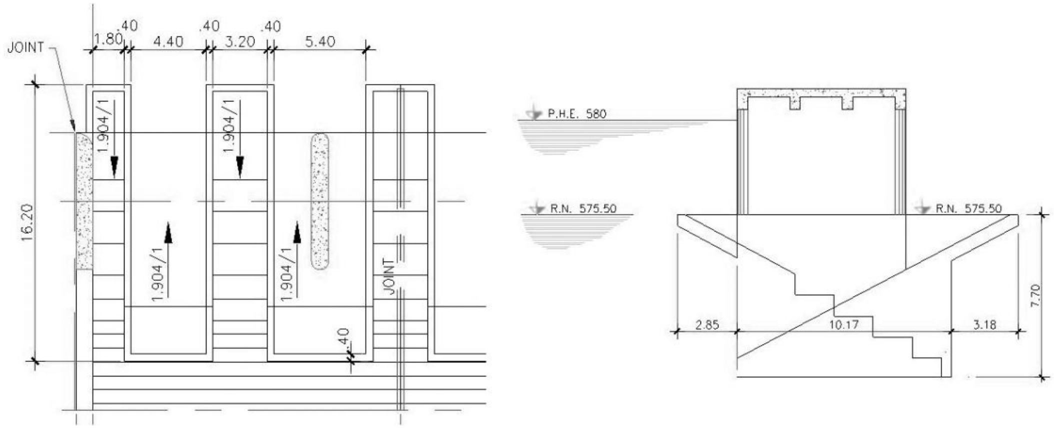

Figure 6: Partial plan view and typical cross section of the Ouldjet Mellegue PKW - Dimensions in m

Figure 7: Aeration of the flow downstream of the ogee crested weir (a), PKW 1 (b) and PKW 2 (c) – Discharge of 50 l/s