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Submerged flow regimes of Piano Key weir

F. Belaabed & A. Ouamane
Laboratory of Hydraulic planning and Environment, University of Biskra, Algeria

ABSTRACT: The piano keys weir can operate in two different flow conditions, in free flow and submerged flow by its use. It can be used to protect the dam against the extreme floods, to measure or control the flow in channels and regulate the flow in a river. As the free flow condition has been studied extensively, it was essential to study the PK-Weir in submerged conditions, basing primarily on theoretical analysis supported by experimental analysis and taking as a reference the linear weir. The obtained results showed a concordance between the theoretical development and experimental results.

1 INTRODUCTION

The spillway is regarded as one of the most important hydraulic infrastructures; this returns to its multifunction, it is often used as component of discharge control and spillway in the rivers. It can be designed in several forms depending on the characteristics required, namely, the dimensions and the profile of the cross-section, the shape of the indentation, the provision in relation to the direction of flow, and the upstream and downstream conditions of the flow.

Based on these last; there are two types of weirs according to the conditions of their operation. The first type corresponds to the free flow weir when water level the downstream does not influence on the flow to the upstream, as well, the aquifer is assumed to be free (Fig. 1-a).

The second type corresponds to the submerged weir when the water level downstream affects the water level upstream (Fig. 1-b).

The flow on the weirs in submerged conditions has been the subject of study in 1947 by Villemonte who has conducted an analysis theoretical and experimental for different forms of the sharp crested weirs. This study was based on simplifying assumptions in order to express the submerged flow by

a- Free flow

b- Submerged flow

Figure 1. Definition of hydraulic parameters for the weir under free and submerged flow conditions.

Submerged flow
– H^*: upstream total head; – h^*: upstream piezometric head;
– H_d: downstream total head; – h_d: downstream piezometric head.
Free flow
– H_o: upstream total head; – h_o: upstream piezometric head.

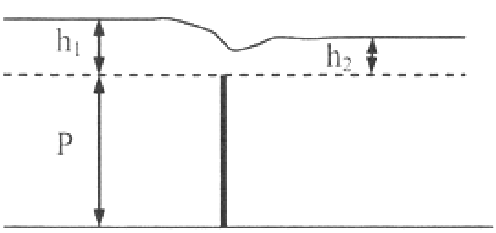


Figure 2. Description of submerged flow according Villemonte (1947).

a mathematical relationship. As well, it has been assumed that the flow on the submerged weir is composed of two parts, the first with a free flow under an effective load equal to the difference in the upstream and downstream levels, and the second part with a submerged orifice flow operating also under a load equal to the difference in the upstream and downstream levels. The second assumption, considers that the net discharge on the weir is the difference in the free flow discharge due to the upstream head h_1 minus the free flow discharge due to the downstream lead h_2 (Fig. 2).

$$Q = Q_1 - Q_2 \tag{1}$$

This last relationship can be written in the form:

$$\frac{Q}{Q_1} = 1 - \frac{Q_2}{Q_1} \tag{2}$$

The experimental tests carried out by Villemonte (1947) have shown that Q/Q_1 is related functionally to $(1 - Q_2/Q_1)$ but that the appropriate function is not the simple linear equation as presented in equation (2). However, it can be expressed by a relationship of the form:

$$\frac{Q}{Q_1} = f\left(1 - \frac{Q_2}{Q_1}\right) = k\left(1 - \frac{Q_2}{Q_1}\right)^m \tag{3}$$

By substituting in the equation (3) Q_1 and Q_2 by the universal discharge relationship $Q_i = C_i h_i^{ni}$, and considering the coefficients C_i and the exponent constant for a given Weir, the relationship (3) becomes:

$$\frac{Q}{Q_1} = k\left(1 - \frac{h_2}{h_1}\right)^m \tag{4}$$

The analysis of the results of tests by the method of the arithmetic mean has enabled Villemonte (1947) to develop a general relationship (5), which expresses the submerged discharge for the sharp crested weir.

The constant k and the exponent m, which account interaction effects, were determined separately for each type of weir by the method of algebraic averages. The results of the numerical analysis for the seven types of weirs tested by Villemonte have shown that the constant k is equal to 1.0 and the exponent m is equal to 0.385 for a range of submergence practice from 0.00 to 0.90.

Thus, the expression in parentheses in the relationship (4) is only the coefficient of reduction of flow in the submerged conditions compared to the free flow.

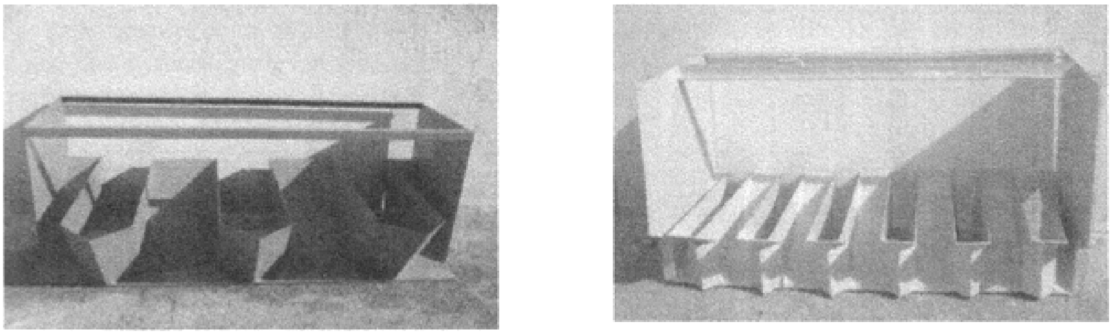
According to King (1954), this coefficient may be expressed also by the coefficient of submergence K.

$$K = \frac{Q_s}{Q_f} = \left[1 - \left(\frac{h_d}{h^*}\right)^n\right]^{0.385} \tag{5}$$

where K = coefficient of submergence; Q_s = discharge in submerged flow conditions; Q_f = discharge in free flow conditions; h_d = downstream total head; h^* = upstream total head; and n = exponent in free flow equation and numerator of submerged flow equation.

Table 1. Geometrical characteristics of the experimented model

Model of weir	n_0	n	L cm	W cm	W_0 cm	W_i cm	B cm	B_0 cm	B_i cm	B_b cm	$P_0 = P_i$ cm
PK-Weir model A	A2m	1.5	266	66	18	15	47	12	12	23	20
PK-Weir model A	A1	3	197	33	9.5	7	41	10.25	10.25	20.5	15


a- PK-Weir type A2m

b- PK-Weir type A1

Figure 3. Model of PK-Weir.

– Proportional weir: $n = 1$ – rectangular weir without contraction: $n = 1.5$
– Parabolic weir: $n = 2$ – triangular weir: $n = 2.5$

The K coefficient represents a reduction coefficient, which must be applied to the free flow discharge for obtain the discharge in the submerged conditions for a given weir. This coefficient depends on the type of weir and cannot be generalized.

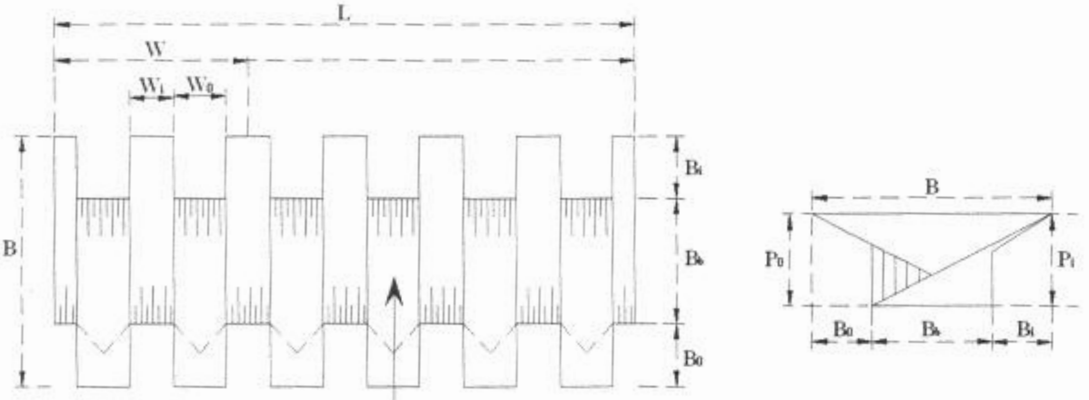
The effect of the submergence on the labyrinth weir and PK-Weir has been studied by Tullis (2006), (2012) which determined experimentally the effect of submergence on the flow of these two types of weirs. The comparison of the obtained results on the two types of weirs has revealed that the PK-Weir seems to be relatively more efficient than the labyrinth weir for the low levels of submergence ($S < 0.75$). However, this is reversed for the highest levels of submergence. Tullis (2012) has pointed out that for the PK-Weir the module of submergence increases as the ratio H_0/P increases. The work which has been carried out by Ho Ta Khanh (2012) has shown that in a hydraulic point of view, the differences between the rectangular labyrinth weir and PK-Weir of types A and D are not very important, but with a slight advantage for the PK-Weir of type D for the strong floods.

Recently, an experimental and theoretical study has been conducted at the University of Biskra. This one represents continuity to that of Belâabed et al. (2011). This study has been based mainly on the theoretical analysis supported by an experimental investigation. As well, two models of PK-Weir have been tested to accomplish this work. The geometric characteristics of these models are listed in the Table 1.

2 EXPERIMENTAL PROGRAM

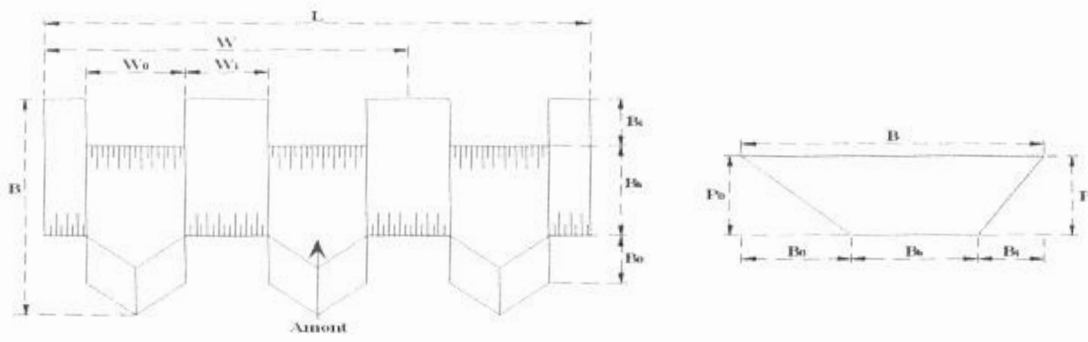
The experimental study conducted on the two models of PK-Weir was realized out in conditions of upstream approach with lateral contraction. Thus, the tests have been conducted in an experiment station of reduced hydraulic models made up of three channels of different sections. An upstream channel of 01 meter in width which simulates the flow in a river, followed by a center channel of 04 meters in width which simulates a reservoir and in its downstream end a channel with a 02 meters in width which simulates the discharge channel. The model of PK-Weir is installed at the exit of the center channel (reservoir), whose waters are discharged into the discharge channel (Fig. 6).

The experimental procedure has been as follows: after having fixed the flow which passes through the channels, we measure the level of water upstream in the free flow conditions. While holding the constant discharge, we are increasing the water level downstream of the PK-Weir by the installation



a- Plan view b- Cross section

Figure 4. Geometrical configuration of the model A1.



a- Plan view b- Cross section

Figure 5. Geometrical configuration of the model A2m.

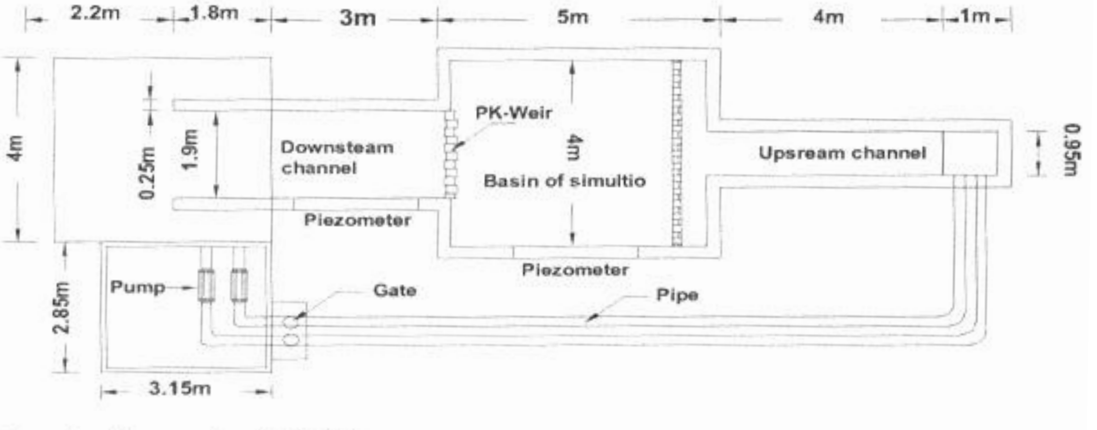


Figure 6. The experimental facility.

of a sill or the closure of a gate which is located at the downstream end of the reception channel. After stabilization of the flow we take the measurements of water depths upstream and downstream of the tested model. Once this operation is carried out we increase another time the height of the sill or the closure of the gate to increase the downstream level and we operate in the same way as previously.

3 EXPERIMENTAL RESULTS

The experimentation on reduced model is sanctioned by results that require an interpretation. In this study, these results are expressed either by the relative upstream head (H^*/H_0) according to the relative downstream head (H_d/H_0) or by the coefficient of submergence (Q_s/Q_f) depending on (H_d/H^*).

3.1 *Effect of the discharge on the submergence of the PK-Weir*

The model of PK-Weir type A2m which is characterized by the continuous overhangs to the base of the weir has been the subject of experimentation for eight values of fixed discharge. The results of these tests have been represented graphically in the form of $H^*/H_0 = f(H_d/H_0)$. From this graphical representation (Fig. 7) we can see that for the different values of discharge, the eight dimensionless curves are similar and confused, particularly for the curves which correspond to large values of flow. As well, we can say that in the case of the submerged flow, the variation of upstream level is done in a proportional manner in relation to the downstream level whatever the flow. This can be also noted for the results of the standards model of PK-Weir type A (Fig. 8).

3.2 *Comparison of the results obtained on the different models*

The geometry of the PK-Weir may take several configurations which can undoubtedly have effects on the flow. Thus, a comparison of the results obtained on the two tested models was made. It is to be noted that the geometry of the two models is different in particular, the form of the overhangs. The graphic representation of the relative upstream head according to the relative downstream head shows a discrepancy between the two curves of the order of 15% for the lower values of H_d/H_0

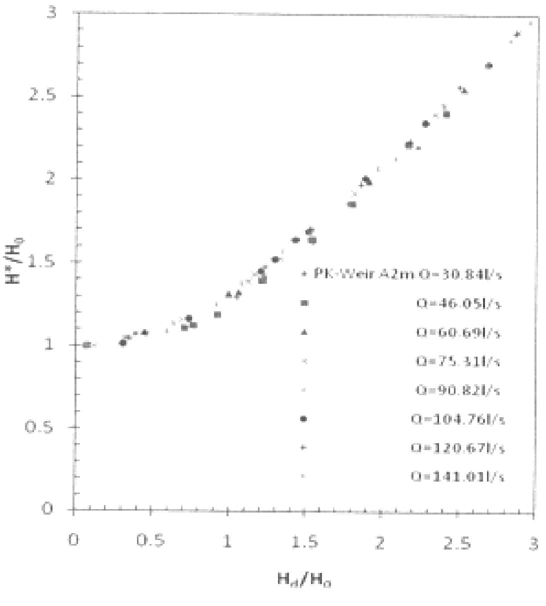


Figure 7. Relative upstream head according relative downstream head (model type A2m).

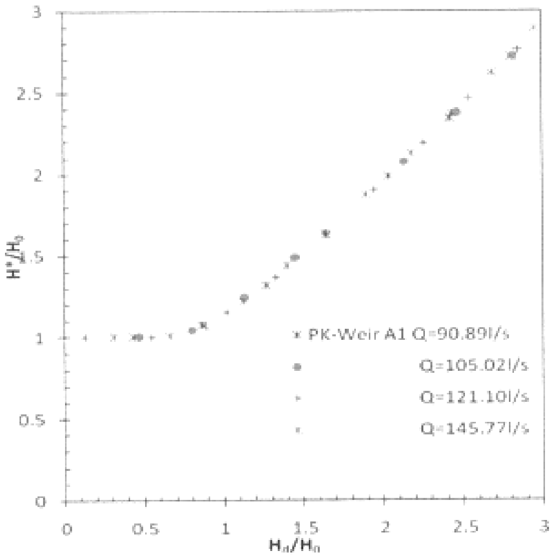


Figure 8. Relative upstream head according relative downstream head (model type A1).

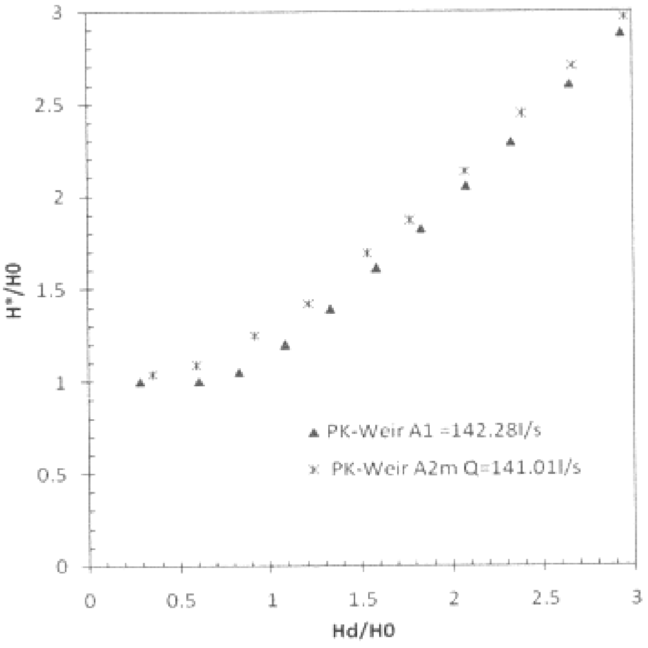


Figure 9. Comparison of the effect of submergence between the PK-Weir type A2m and A1.

and approximately 3% for the high values of H_d/H_0. This discrepancy shows that the effect of the submergence of the PK-Weir A2m is more expressed than that of PK-Weir A1 (Fig. 9). It is also to be noted that the effect of the submergence on the flow upstream of PK-Weir A2m began when the relative downstream head exceeds 0.5 ($H_d/H_0 > 0.5$). However, for the PK-Weir A1, this effect is observed only for the values of the relative downstream head greater than 0.8 ($H_d/H_0 > \sim 0.8$).

3.3 *Mathematical relationship of the coefficient of submergence*

Based on the study of Villemonte which relies on simplifying assumptions, a numerical analysis of the obtained experimental data has been carried out. This analysis had for objective to determine a mathematical relationship which expresses the coefficient of submergence of the PK-Weir A2m.

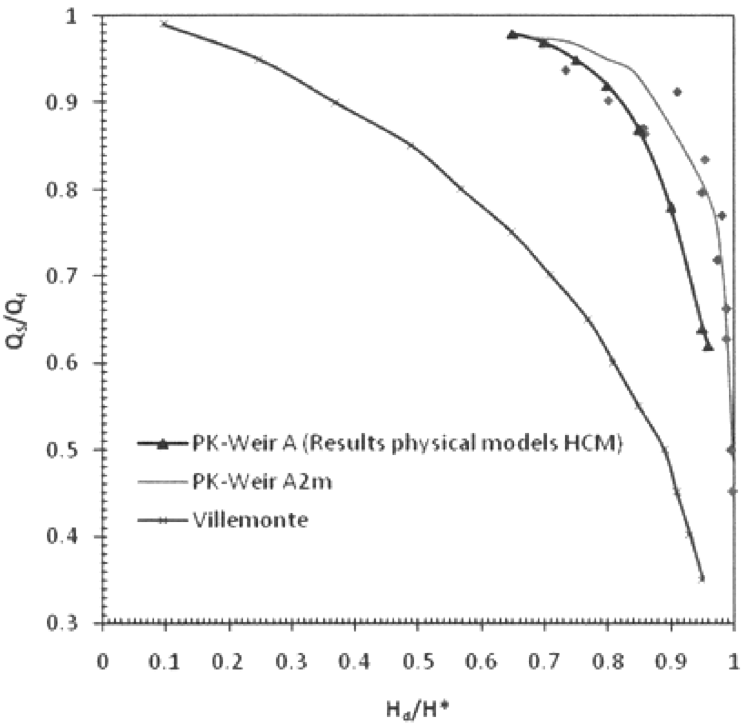


Figure 10. Discharge for submerged Weir.

This analysis has also concerned the PK-Weir type A (according to the data of Ho Ta Khanh, 2012). Consequently, the following relationships were obtained.

Rectangular Weir (Villemonte):

$$K = \frac{Q_s}{Q_f} = \left[1 - \left(\frac{h_d}{h^*}\right)^{1.5}\right]^{0.385} \tag{6}$$

PK-Weir type A2m:

$$K = \frac{Q_s}{Q_f} = 1.158\left[1 - \left(\frac{h_d}{h^*}\right)\ \right]^{0.126} \tag{7}$$

$0.68 \leq H_d/H^* \leq 0.99$

PK-Weir type A (Results of physical models HCM):

$$K = \frac{Q_s}{Q_f} = 1.289\left[1 - \left(\frac{h_d}{h^*}\right)\ \right]^{0.225} \tag{8}$$

$0.65 \leq H_d/H^* \leq 0.96$

The first relationship was developed by Villemonte for a linear rectangular weir without lateral contraction. While the last two relations (6) and (7) have been developed by a numerical analysis of the obtained data on the model A2m and the obtained data on the model A by Ho Ta Khanh (2012).

The graphical representation $Q_s/Q_f = f(H_d/H^*)$ (Fig. 10) for the three models of Weir (PK-Weir A2m, PK-Weir A (HCM) and the spillway rectangular (Villemonte) shows that the effect of the submergence begins from a low value of the ratio H_d/H^* for the linear rectangular weir. However, the effect of the drowning does not manifest that later for the two PK-Weirs A2m and A, for the values $H_d/H^* > 0.5$. This observation shows that the importance of the effect of the submergence depends on the weir type. This study fact appears that the PK-Weir is better adapted to function in conditions of submerged flow that the linear weirs.

4 CONCLUSION

This study is primarily interested in the effect of the downstream level on the upstream level in submerged flow conditions. The tests carried out on two models of PK-Weir have shown that the downstream conditions can affect the upstream flow of the PK-Weir. This influence has been demonstrated that it is characterized by a proportional variation between the upstream and the downstream whatever the importance of the discharge. It was also found that the variation of the relative downstream head compared to the relative upstream head is done in a proportional manner for the different discharge on the PK-Weir A2m.

The PK-Weir with overhangs continued up to the base (A2m) seems to be more exposed to the submergence that the PK-Weir standard type A.

The PK-Weir has the advantage to be better adapted to function in conditions of submerged flow, however, the linear weir is more susceptible to submergence. As well, the importance of the effect of the submergence depends on the type of weir.

REFERENCES

Belaabed, F., Ouamane, A. 2011. Contribution to the study of the Piano Key Weirs submerged by the downstream level, *Labyrinth and piano key weirs-PKW 2011*: 89–95. London: CRC Press.

Dabling, M.R., Tullis, B.P. 2012. Piano Key Weir Submergence in Channel Applications. *International Workshop on Piano Key Weir for In-Stream Storage and Dam Safety (PKWISD-2012)*, New Delhi, India.

Ho Ta Khanh, M. 2012. Utilization of Piano Key Weirs for low barrages. *Hydro 2012*, Bilbao, Spain

Lopes, R., Matos, J., Melo, J.F. 2009. Discharge capacity for free flow and submerged labyrinth weirs. *Proc. 33rd IAHR congress*, Vancouver, Canada.

Ouamane, A., Lempérière, F. 2010. Study of various alternatives of shape of piano key weirs, *HYDRO 2010 – Meeting Demands in a Changing World*, Lisbon, Portugal.

Tullis, B.P. 2006. Predicting submergence effects for labyrinth weirs, *International Symposium on Dams in the Societies of the XXI Century*. Barcelona, Spain.

Tullis, B.P., Young, J.C., Chadler, M. A. 2007. Head-Discharge Relationships for Submerged Labyrinth Weir. *ASCE Journal of Hydraulic Engineering*, 133(3), 248–254.

Villemonte, J.R. 1947. *Submerged weir discharge studies*. Eng. News-Rec.