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Experimental investigation of submerged flow over piano key weir

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Abstract
Extensive experimental investigation has been performed to analyse the behaviour of piano key weir under submerged flow conditions. More than 2500 runs were performed on 14 physical models in an experimental rectangular flume, 15 m long and 0.3 m by 0.45 m cross-section. Effect of submergence phenomenon on the discharge capacity was studied for different discharge values. It was found that the discharge reduction factor Cs is mainly influenced by the submergence factor S. This effect starts when S is greater than the modular submergence limit which proved to be around 0.4 to 0.6. Models with different geometrical parameters were compared to each other and final conclusions about their effect on discharge capacity were achieved. However, the influence of all the geometrical parameters was small (less than 12%).

Keywords: Physical modelling; Piano key weir; Submerged flow; Discharge coefficient; Discharge reduction factor; Submergence factor; Modular submergence limit.

1. Introduction
Piano Key Weir (PKW) is a new type of labyrinth weirs that combines the interest of labyrinth layout with the use of sloped floors and overhangs in order to develop an innovative geometry that helps to overcome the problems of traditional labyrinth weirs. The new alternative stands out from the previous type with firstly, its structural simplicity and being easy to build with local resources in all countries, and secondly, its suitability for installation on top of existing or new gravity dams as well as on earth dams due to its reduced footprint area [1].
Submergence occurs when the downstream water depth exceeds the crest level forcing the upstream head to increase. This means a *reduction* in PKW capacity because higher heads will be required to pass a given discharge relative to the heads in free flow condition.
This article studies the performance of PKW under submerged flow condition. Experimental study has been conducted using 14 physical models in an experimental flume where the submerged condition was realized using a sluice gate. Each model represented a variation in the geometrical parameters for the purpose of examining their influence on the submergence phenomenon. Free flow testing was conducted at first, and then submerged conditions were achieved using a sluice gate. The results are presented and compared to each other to

emphasize the effect of the hydraulic and geometrical parameters on the submerged flow behaviour.

2. Description of PKW geometry and submerged flow condition

The piano key weir consists of simple rectangular layout (similar to the keys of piano); thus, forming a labyrinth weir with zero side wall angle. The alternative arrangement of its sloped floors in both upstream and downstream directions is an important characteristic as it creates an overhang (or cantilever) and, hence, reduces the weir footprint area.

Pralong et al [2] have set a standard nomenclature to simplify the study for researchers around the world. Figure 1 illustrates a general view of PKW along with the notations which are described in Table 1.

The weir may be constructed on a dam (or any height), therefore, in addition to the height P, another notation that represents the dam height was utilized, namely P_d.

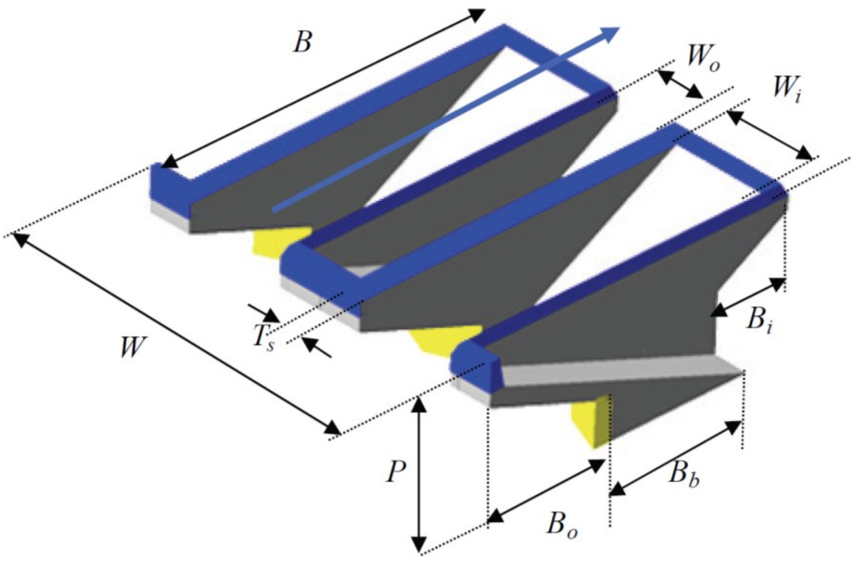

Figure 1. Sketch of PKW geometry [2].

Table 1. Terminology of PKW geometrical parameters [2].

Parameter symbol	Meaning
B	Upstream-downstream length of the PKW, $B=B_b+B_i+B_o$
B_o	Upstream (outlet key) overhang length
B_i	Downstream (inlet key) overhang length
B_b	Base length
P	Height of PKW measured from the crest (including possible parapet walls)
P_d	Dam height (or any platform under the PKW)
W	Total width of the PKW
W_i	Inlet key width (sidewall to sidewall)
W_o	Outlet key width (sidewall to sidewall)
T_s	Sidewall thickness
T_i	Horizontal crest thickness at inlet key extremity
T_o	Horizontal crest thickness at outlet key extremity
L	Total developed length along the overflowing crest axis

When the PKW is operating under free flow condition, the discharge is determined using the standard rectangular weir equation [3]:

$$Q = C_{dW}\frac{2}{3}\sqrt{2g}WH_o^{1.5} \quad (1)$$

where: Q is the discharge, C_{dW} is discharge coefficient, g is the gravitational acceleration, W is the channel width and H_o is the total head. However, when submergence occurs, the free flow discharge should be modified by a reduction factor so as to calculate the actual value of discharge, therefore:

$$C_s = \frac{Q_s}{Q} \quad (2)$$

where: C_s is the reduction factor, Q_s is the actual discharge during submerged flow condition and Q is the discharge calculated by substituting the total upstream head during submerged flow, H_u, in equation 1. Figure 2 illustrates the two flow conditions and their related parameters which are defined in Table 2.

C_s is dependent on the ratio of the total downstream water head above the crest level H_d to the upstream one H_u, i.e. the ratio H_d/H_u which is called in the literature the *Submergence Factor* and denoted by S. The submergence factor is a measure of the submergence "status" applied on the weir. Its value ranges from 0.0 to 1.0. When S=0, the weir is considered in a free flow condition since H_d=0. When S=1, the weir is in fully submerged condition since H_d=H_u, and the weir is no longer working in this case as a control structure.

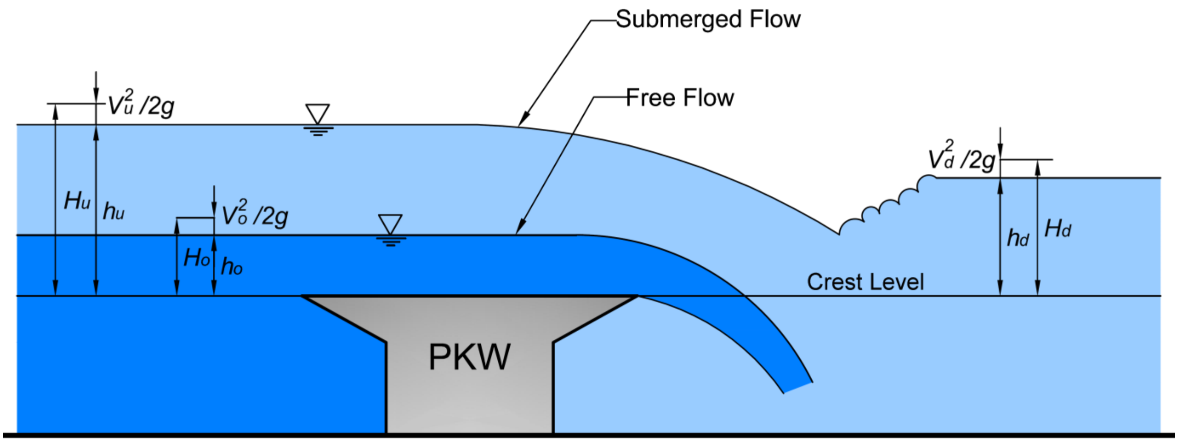

Figure 2. Flow conditions over piano key weir.

Table 2. Parameters used to describe the flow condition over PKW.

Parameter symbol	Meaning
H_u	Total head over crest level upstream from weir during submerged flow condition
h_u	Upstream flow depth over crest level during submerged flow condition
H_d	Total head over crest level downstream from weir
h_d	Downstream flow depth over crest level
H_o	Total upstream head over crest during free flow condition
h_o	Upstream flow depth over crest during free flow condition
V_u	Upstream flow velocity during submerged flow condition
V_d	Downstream flow velocity during submerged flow condition
V_o	Upstream flow velocity during free flow condition

Submergence phenomenon causes negative effect on discharge capacity. However, this effect does not start immediately when the tail water rises above the crest level, but it rather starts when the submergence factor S reaches a certain value known as the *Modular Submergence Limit* or the *Submergence Threshold*. The study of Kabiri-Samaini and Javaheri [4] states that this limit is S=0.6. According to this conclusion, the value of C_s is considered 1.0 (i.e. free flow behaviour) as long as S<0.6.

A study by Dabling [5] considered a model having the properties preferred by Lempérière [6] which are: (L/W=5, W_i/W_o=1.25, B/P=2.4, B_i/B=0.25, B_o/B=0.25). The study included also another model similar to the first but with a circular nose under the upstream overhang and a parapet wall with a height equal to

(0.128*P*). It was concluded that the modular submergence limit for both models is approximately S=0.48. This means that as long as S<0.48, the PKW performs as free weir and C_s=1.0. The study included testing these two models under different ratios of H_o/P. Generally, it was concluded that at higher values of H_o/P, larger values of C_s (closer to 1.0) are obtained. This behaviour was revealed from both models.

Cicero and Delisle [7] studied three PKW models of types A, B, and C. They concluded that the modular submergence limit increases with the increase of the downstream overhang B_i. The model type-B having B_i/B=0 has its modular limit at S≈0.2, while type-A at S≈0.5, and type-C at S≈0.6.

A comparison between the three models (of types A, B, and C) in terms of their discharge capacity was also made in their study. The type-C was less efficient than type-A within the range of (0<S<0.9). The type-B was more efficient than type-A for S<0.5, and more efficient than type-C for S<0.8. In addition, the three models were compared with sharp crested and long broad-crested weirs. The linear weirs were much less efficient than PKWs. The percentage losses in discharge relative to type-A model were from 50% to 70% for sharp-crested weir and from 50% to 60% for broad-crested weir.

3. Experimental setup and testing procedure

Experimental tests were conducted in a 15 m long, glass-walled flume having a rectangular section of 0.3 m wide by 0.45 m deep. Flume discharge is measured by means of a pre-calibrated sharp-crested rectangular weir. The flume is equipped with a rolling point gauge apparatus with accuracy of ±0.5 mm. The flume has a closed-loop water system. A main tank, of 4.5 m^3 capacity, is located at the downstream end of the flume. Water is conveyed from the main tank to an inlet tank, of 0.5 m^3 capacity, at the upstream end by means of a pump having maximum discharge of 36 litre/sec.

Fourteen physical models were prepared in this investigation. Firstly, a standard PKW model that agrees with the limitations of [6] was selected for purpose of comparison. These limitations are: (L/W=5, W_i/W_o=1.25, B/P=2.4, B_i/B=0.25, B_o/B=0.25). This model is denoted by (M) in this article.

The other 13 models represent different geometrical parameters. Table 3 presents these models where each parameter was given different values while the other parameters kept constant.

All models were manufactured of 2.5 mm thick acrylic glass sheets cut with a CNC machine. They are made of 2-units PKW with flat-top crest. Dimensions of models are given in Table 4.

Each model was fixed firmly to the flume bed with application of enough quantity of silicon rubber to prevent movement and ensure water tightness. Models were located at the mid-section of the flume to guarantee that uniform flow is developed and to avoid the downstream effects.

Table 3. Geometrical parameters of PKW models.

Model No.	Model Notation	L/W	W_i/W_o	B/P	B_i/B	B_o/B	P_d/P
1	M	5.0	1.25	2.4	0.25	0.25	0.6
2	L3	3.0	1.25	2.4	0.25	0.25	0.6
3	L6	6.0	1.25	2.4	0.25	0.25	0.6
4	W0.4	5.0	0.40	2.4	0.25	0.25	0.6
5	W1	5.0	1.00	2.4	0.25	0.25	0.6
6	W2.5	5.0	2.50	2.4	0.25	0.25	0.6
7	P2	5.0	1.25	2.0	0.25	0.25	0.6
8	P3	5.0	1.25	3.0	0.25	0.25	0.6
9	B_i0	5.0	1.00	2.4	0.00	0.25	0.6
10	B_i0.5	5.0	1.00	2.4	0.50	0.25	0.6
11	B_o0	5.0	1.00	2.4	0.25	0.00	0.6
12	B_o0.5	5.0	1.00	2.4	0.25	0.50	0.6
13	P_d0	5.0	1.00	2.4	0.25	0.25	0.0
14	P_d1.5	5.0	1.00	2.4	0.25	0.25	1.5

Table 4. Dimensions of the PKW models in this study (centimetres).

Model Notation	B	P	B_i	B_o	W_i	W_o	P_d
M	30.3	12.6	7.6	7.6	8.06	6.44	7.6
L3	15.3	06.4	3.8	3.8	8.06	6.44	3.8
L6	37.8	15.7	9.4	9.4	8.06	6.44	9.4
P2	30.3	15.2	7.6	7.6	8.06	6.44	9.1
P3	30.3	10.1	7.6	7.6	8.06	6.44	6.1
W0.4	30.3	12.6	7.6	7.6	4.14	10.4	7.57
W1	30.3	12.6	7.6	7.6	7.20	7.20	7.6
W2.5	30.3	12.6	7.6	7.6	10.4	4.14	7.6
B_i0	30.3	12.6	0.0	7.6	7.2	7.2	7.6
B_i0.5	30.3	12.6	15.1	7.6	7.2	7.2	7.6
B_o0	30.3	12.6	7.6	0.0	7.2	7.2	7.6
B_o0.5	30.3	12.6	7.6	15.1	7.2	7.2	7.6
P_d0	30.3	12.6	7.6	7.6	7.2	7.2	0.0
P_d1.5	30.3	12.6	7.6	7.6	7.2	7.2	18.9

Testing procedure starts by conducting free flow condition test for each model. Head-discharge relationship is constructed by recording the water head values associated with different discharges. Then, the downstream water level is raised by lowering the sluice gate at gradual intervals recording the water level at upstream and downstream each time. This is done with nine different discharges. Measurements of water head at upstream and downstream were taken at distances of 32 cm and 120 cm from weir apex respectively; see Figure 3. The sluice gate is continuously lowered until a sufficient relationship between the submergence factor S and the discharge reduction factor C_s is established.

Any reading of water head that is below 3 cm was avoided. This is because readings below this value are influenced by the scale effects (surface tension and viscosity effects) and would not reflect the behaviour of real prototypes [8].

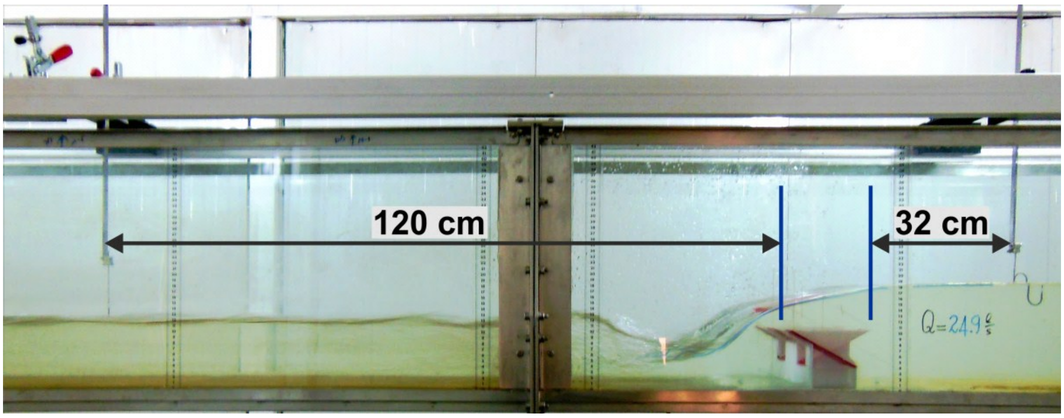

Figure 3. Measurement of upstream and downstream heads during submerged flow condition.

4. Experimental results

When the tail water level starts to rise, submergence of the entire model starts to occur. At first, the air pocket under the downstream overhangs disappears and the hydraulic jump becomes submerged as the tail water level rise gradually. Then, the tail water reaches to a certain value so that the submergence factor reaches the modular limit. After this limit, the upstream water level starts to rise as the tail water continues to rise. This value of S is related to the discharge capacity since the weir starts to lose its capacity at this point. However, when the tail water depth becomes equal to the upstream depth (i.e. S=1) the model will not work as a control structure because it will be totally submerged. The experiment stops at this point. Figure 4 demonstrates the submerged flow of the model L6 under different submergence factors.

To analyse the results, a C_s vs. S relationship is plotted for each model within the tested discharges. In the following paragraphs, description of the tested models data in order to present the effect of different parameters on C_s.

In order to demonstrate the submergence effect on the discharge coefficient, values of C_{dW} under free and submerged flow conditions are plotted vs. the upstream head ratio H_u/P in Figure 5. The free flow values forms an envelope curve to the submerged flow data where the discharge coefficient starts to decrease by submergence effect. It may be noted that the decrease in C_{dW} happens in small H_o/P ratios (i.e. small discharges) more rapidly than in large values of H_o/P.

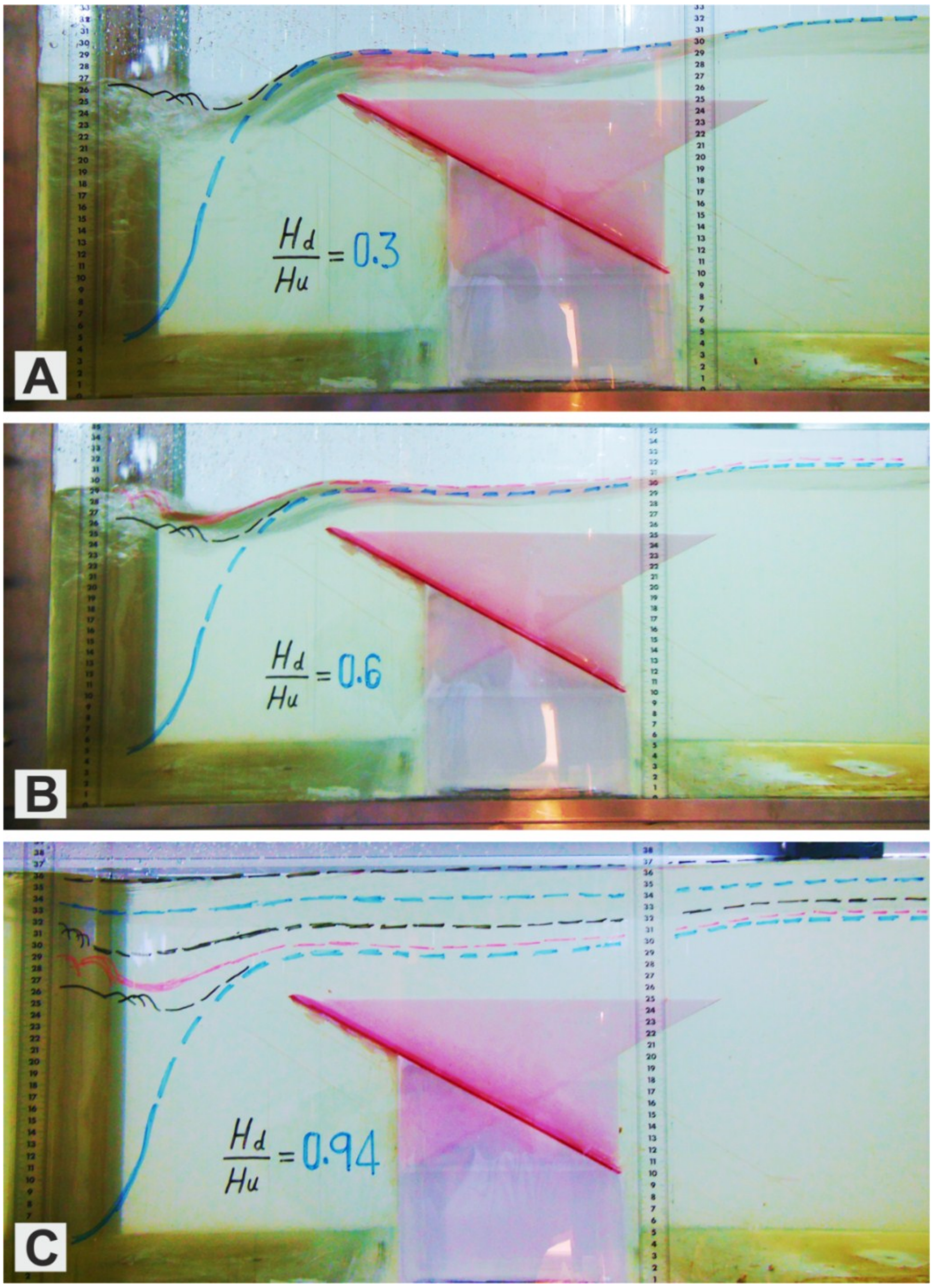

Figure 4. Model L6 under submerged flow with Q=36.26 liter/sec. (A) S=0.3, (B) S=0.6, PKW at modular limit, and (C) S=0.94 almost fully submerged.

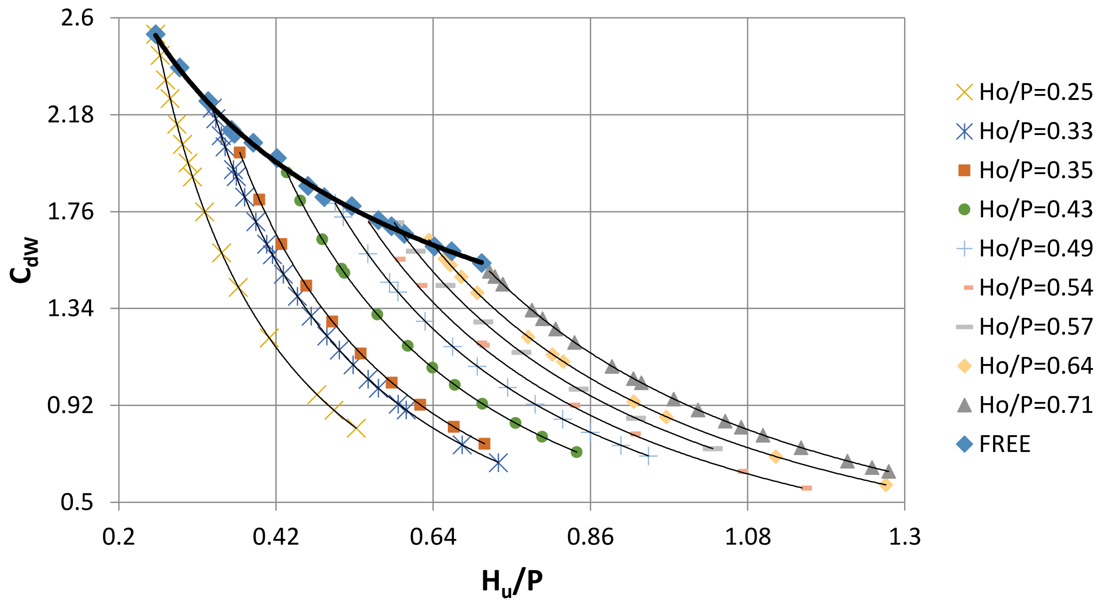

Figure 5. Values of C_{dW} for model M at free and submerged flow conditions.

4.1 Effect of the submergence factor S

Submergence factor S is the main parameter that influence the reduction factor C_s. Figure 6 shows that C_s is equal to 1.0 until the submergence reaches the modular limit at which S=0.5 approximately. Then, C_s starts to decrease gradually and reaches its minimum value (around 0.4) at full submergence.

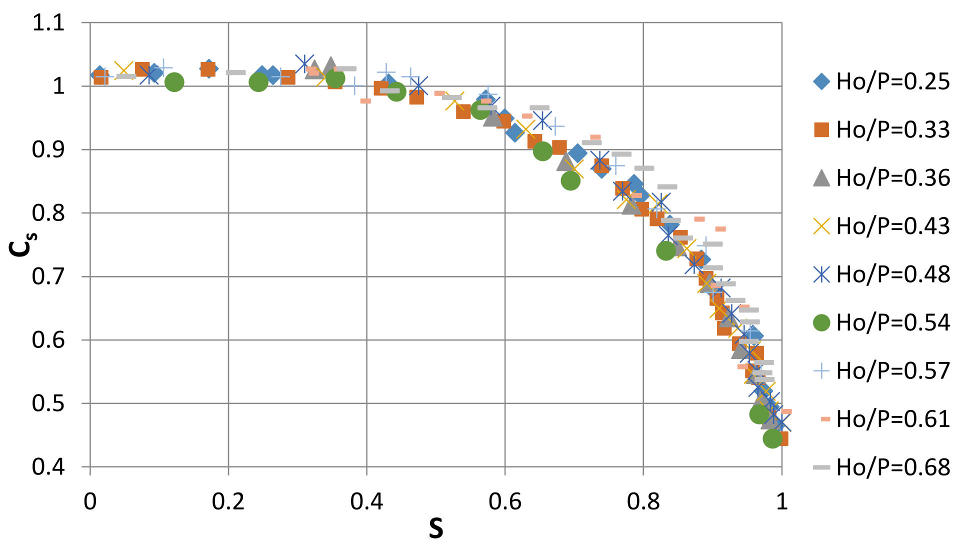

Figure 6. Variation of C_s vs. S for model M at different H_o/P ratios.

The modular limit may be changed depending on the PKW geometry. Generally it ranges between (0.4 and 0.6) although it may be less than that. However, it may be considered equal to 0.5 as a reliable conservative estimate.

An abnormal behaviour has been observed during submerged flow tests. When submergence starts by the rise of the downstream head H_d and while S is below the modular submergence limit, the upstream head decreases slightly indicating a small increase in discharge capacity. This makes C_s slightly greater than 1.0 as shown in the Figures 6, 8, to 13. However, when S exceeds the modular limit, the capacity starts to decrease. Similar observation is reported by Dabling [5].

To emphasize the variation of C_{dW}, the plot of C_{dW} vs. S of model M is presented in Figure 7. It is obvious how the value of C_{dW} remains unchanging as long as S is less than the modular limit (which is equal to about 0.5). After this limit all the curves of different H_o/P ratios decrease and tend to converge at single C_{dW} value at full submergence. Again, the rate of change of low discharges curves is greater than that of large discharges.

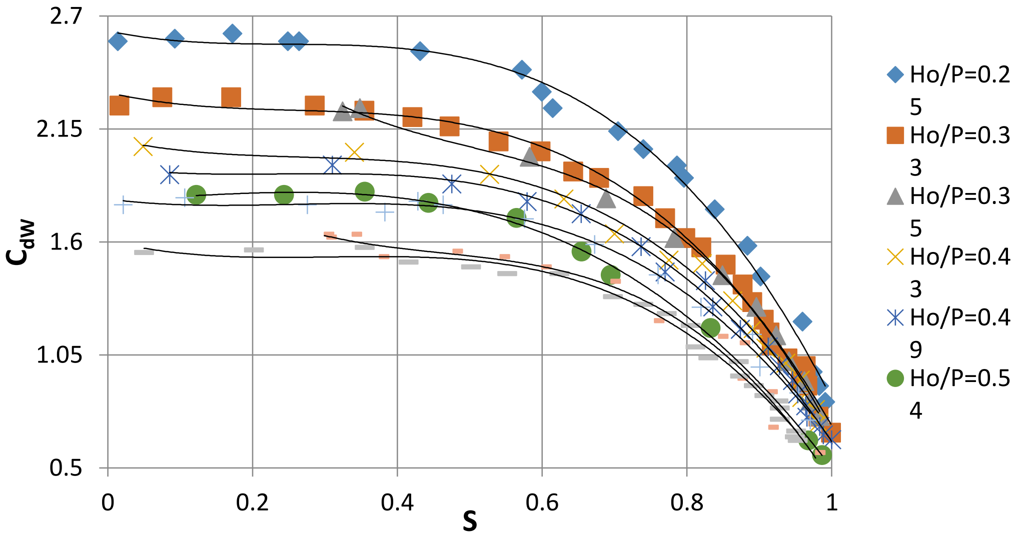

Figure 7. Variation of C_{dW} vs. S for model M at different H_o/P ratios.

4.2 Effect of H_o/P ratio

Referring to Figure 6, it may be observed that for different values of H_o/P (discharges), the nine curves representing C_s are generally similar. However, values of C_s at large H_o/P ratios tend to increase slightly (about 7% over small H_o/P ratios). This means that at large discharges, less capacity will be lost due to submergence effect.

This conclusion was confirmed by Dabling [5]. However, some researchers such as Kabiri-Samani and Javaheri [4] and Belaabed and Ouamane [9] considered the slight influence of H_o/P on C_s to be negligible.

4.3 Effect of geometrical parameters

No pronounced influence of the L/W ratio has been observed. Figure 8 shows the variation of C_s vs. S for the three models L3, M, and L6. All the curves are taken at approximately similar values of H_o/P.

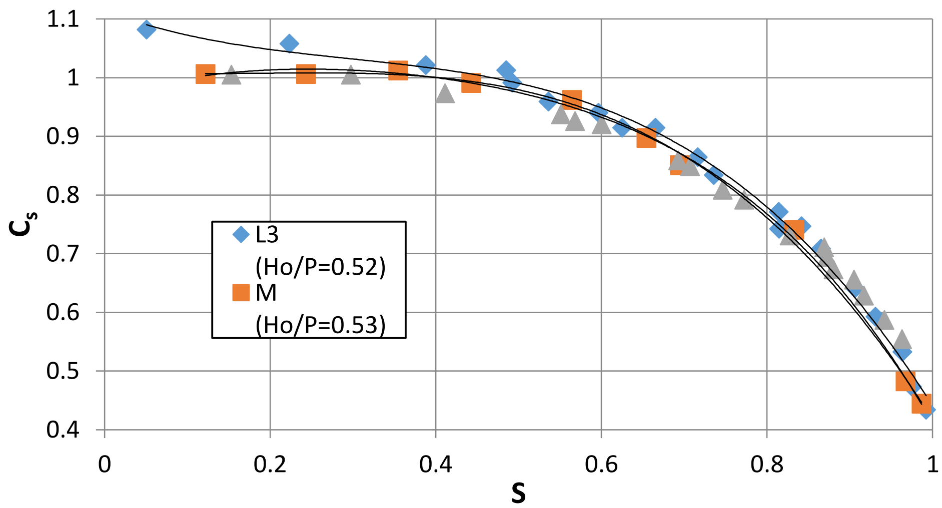

Figure 8. Variation of C_s vs. S for three L/W values.

Influence of W_i/W_o is more pronounced than that of L/W. Figure 9 illustrates the variation of C_s vs. S for four models with different W_i/W_o ratios. Inverse relation between W_i/W_o and C_s is observed. Model W2.5 behaves with less C_s than W1 by a maximum difference of 12%. However, the model W0.4 has greater C_s than W1 by maximum gain of 5%. All the models tend to converge at high submergence factor (S approaching 1.0). It may be also noted that the modular submergence limit of model W2.5 was reduced to about 0.2, whereas the other models start to lose their efficiency at S=0.6 approximately. All tests of model W2.5 showed a modular limit of 0.2 to 0.3.

The parameter B/P has also proved to be of influence on C_s. Figure 10 presents the behaviour of three models with different B/P ratios. It seems that decreasing B/P to 2.0 provides C_s values that are about 5% less than B/P=3.0. Using B/P=2.4 seems similar to B/P=3.0. The modular submergence limit is approximately the same for the three models with a value of about 0.45 to 0.5.

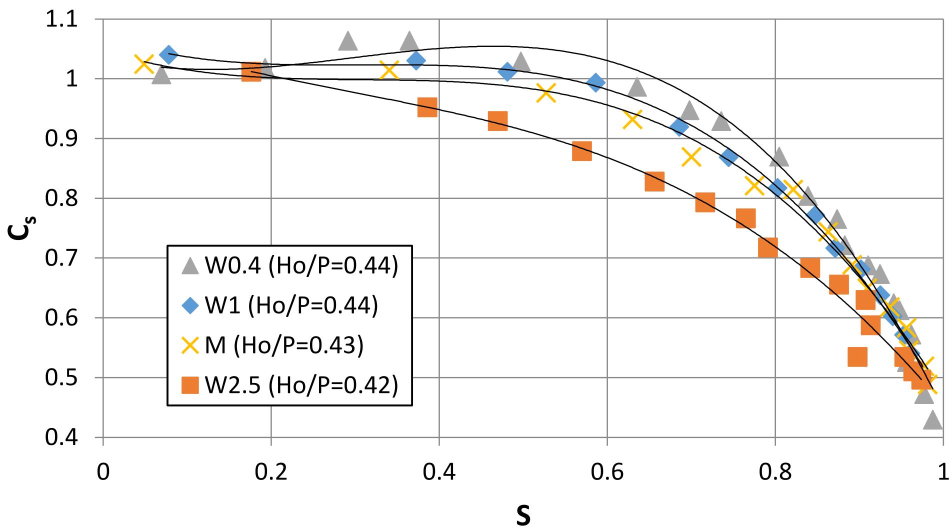

Figure 9. Variation of C_s vs. S for different W_i/W_o values.

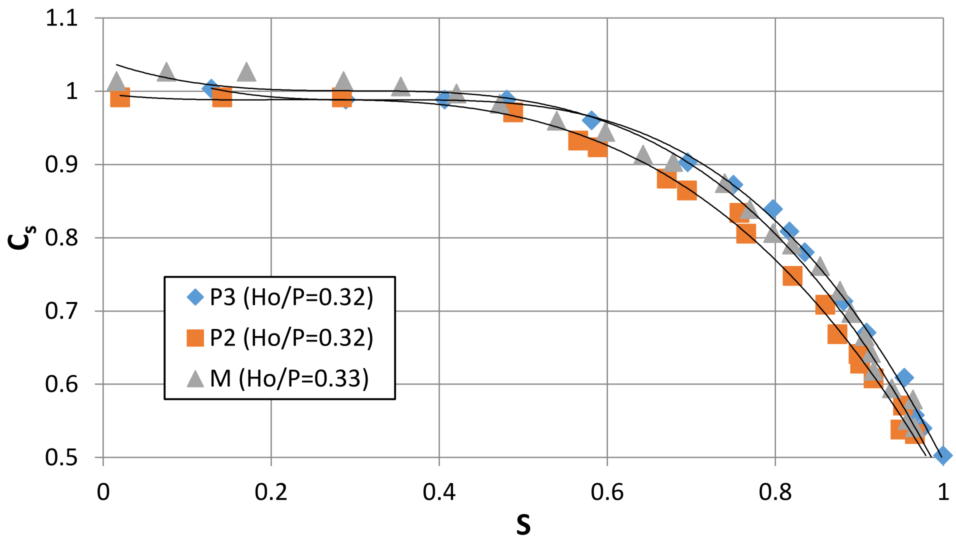

Figure 10. Variation of C_s vs. S for three B/P values.

Influence of B_i/B does not seem very interesting since all the tested models were similar in their behaviour. In Figure 11, although models B_i0 and $B_i0.5$ seem slightly better than W1, their behaviours are very similar. The modular submergence limit is similar for the three models.

Effect of B_o/B on C_s is shown in Figure 12. It seems here that increasing the upstream overhangs have a negative effect on C_s. The curve of model $B_o0.5$ gives results that are 9% less than results of W1. Therefore, upstream overhangs are unfavourable in submerged flow applications. On the other hand the behaviour of the model with no overhangs B_o0 is 9% more than W1 making it more favourable.
Finally, the dam height effect which was tested by the two models P_d0 and $P_d1.5$ in addition to W1. Their behaviour is shown in Figure 13. No pronounced influence was observed when changing the parameter P_d/P; therefore, it is not of interest in the study of submerged flow over PKWs.

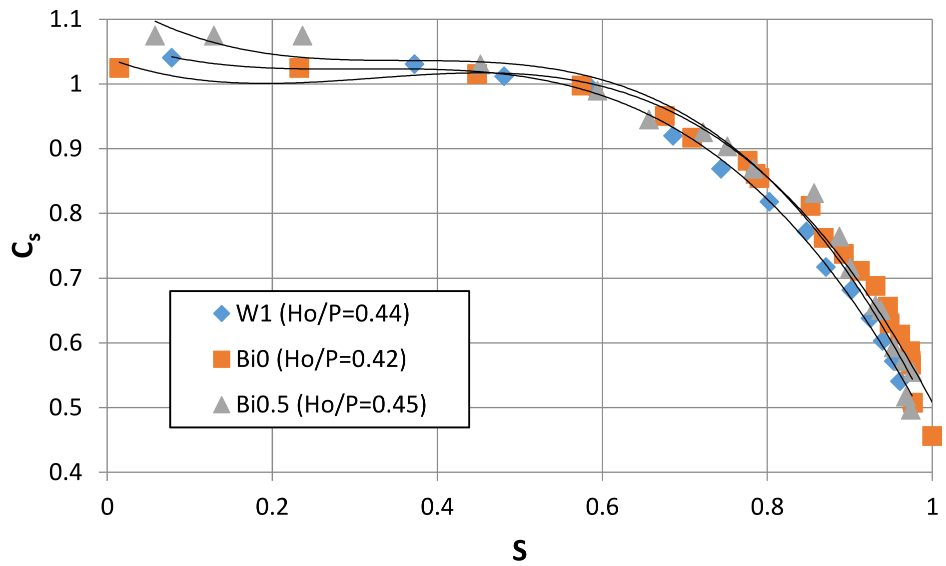

Figure 11. Variation of C_s vs. S for three B_i/B values.

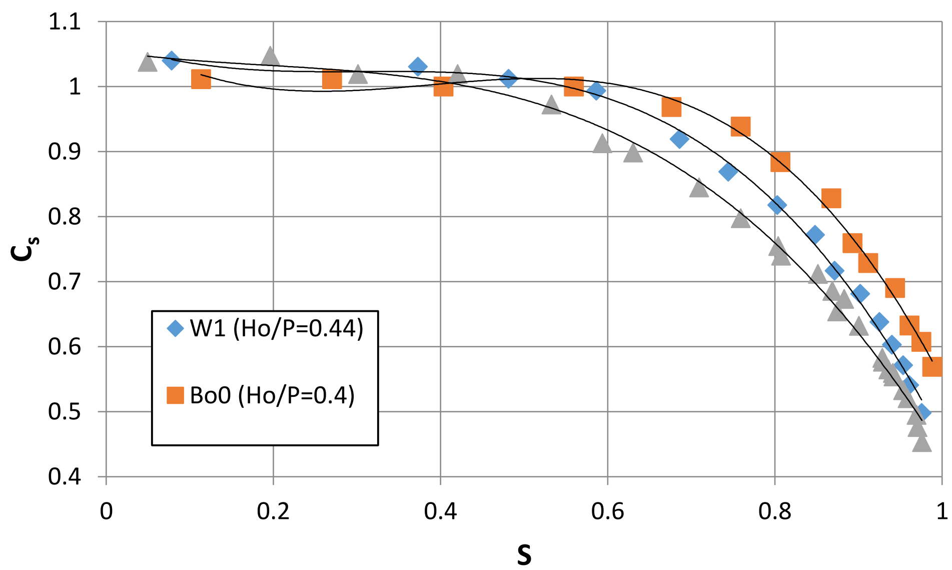

Figure 12. Variation of C_s vs. S for three B_o/B values.

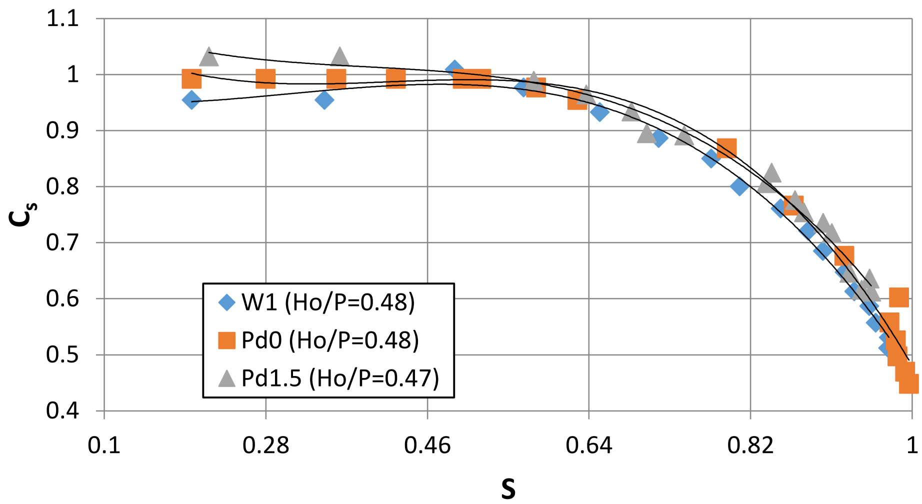

Figure 13. Variation of C_s vs. S for three P_d/P values.

5. Conclusion

- Discharge reduction factor C_s is influenced mainly by the submergence factor S and in less degree by the other PKW parameters. As long as S is below the modular submergence limit, C_s=1.0. But it starts to decrease as S increases until it reaches a minimum value of that ranges from (0.4 to 0.6).
- Value of the modular submergence limit can be considered conservatively as 0.5 for all tested models.
- Influence of H_o/P on C_s is small where high discharges can increase C_s by 7% as maximum effect.
- C_s is influenced very slightly or negligibly ±2% by the parameters: L/W, B_i/B, and P_d/P.
- Increasing W_i/W_o up to 2.5 can reduce C_s by about 12% relative to a model with W_i/W_o=1.0. Whereas decreasing W_i/W_o from 1.0 to 0.4 can increase C_s by 5%.
- Decreasing B/P from 3.0 to 2.0 reduces the value of C_s by about 5%. Thus it is of minor influence.
- The parameter B_o/B has an influence of +9% approximately on C_s when increasing its value from 0.25 to 0.5. But the influence becomes –9% when decreasing its value from 0.25 to 0.0.

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References

[1] Ouamane, A., and Lempérière, F. (2006). Design of a new economic shape of weir. http://www.hydrocoop.org.
[2] Pralong, J., Vermeulen, J., Blancher, B., Laugier, F., Erpicum, S., Machiels, O., Pirotton, M., Boillat, J.-L., Leite Ribeiro, M., and Schleiss, A. J. (2011), "A naming convention for the Piano Key Weirs geometrical parameters", Proceedings of the International Conference Labyrinth and Piano Key Weirs – PKW 2011, Liège, Belgium, CRC Press, London, pp. (271-278).
[3] Schleiss, A. J. (2011), "From Labyrinth to Piano Key Weirs – A historical review", Proceedings of the International Conference Labyrinth and Piano Key Weirs – PKW 2011, Liège, Belgium, CRC Press, London, pp. (3-15).
[4] Kabiri-Samaini, A., and Javaheri, A. (2012), "Discharge coefficients for free and submerged flow over Piano Key weirs", Journal of Hydraulic Research (Taylor & Francis Group), Vol. (50), No. (1) (2012), pp. (114–120).
[5] Dabling, M. R. (2014), "Nonlinear Weir Hydraulics", M.Sc. Thesis, Utah State University, USA, All Graduate Theses and Dissertations, Paper 2189. http://digitalcommons.usu.edu/etd/2189.

[6] Lempérière, F. (2009), "New Labyrinth weirs triple the spillways discharge – Data for an easy design of P.K. Weir", http://www.hydrocoop.org.
[7] Cicero, G. M., and Delisle, J. R. (2014), "Discharge characteristics of Piano Key weirs under submerged flow", Proceedings of the International Conference Labyrinth and Piano Key Weirs II – PKW 2013, Chatou, Paris, France, CRC Press, London, pp. (101-109).
[8] Novak, P., Guinot, V., Jeffrey, A., and Reeve, D. E., (2010), "Hydraulic modelling – an introduction", (1st edition), Spon Press, London.
[9] Belaabed, B., and Ouamane, A. (2011), "Contribution to the study of the Piano Key Weirs submerged by the downstream level", Proceedings of the International Conference Labyrinth and Piano Key Weirs – PKW 2011, Liège, Belgium, CRC Press, London, pp. (89-95).

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