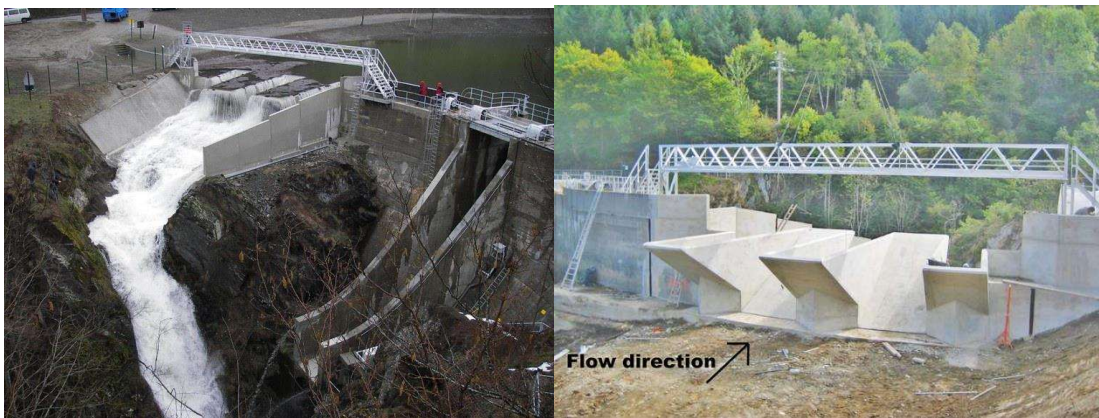


### 2.1 Introduction

Free-flow spillways are simpler and reduce the risk of not opening during high floods, and are safer than gated ones. The discharge through free fall spillways is dependent on the crest length. Research as such has been carried out extensively for increasing the crest length and design a spillway which comprises: (a) a shape which can be both placed on an existing or be built entirely for a new dam, (b) a shape that is structurally simple but stable to construct with general engineering knowledge, (c) increased discharge intensity and (d) more cost-effective.

This research led to the evolution of the family of weirs in long-crested weirs such as diagonal weir, duckbill weir, W-shaped weirs, labyrinth weirs and finally, a new type of weir called Piano Key. The concept of PKW is quite recent and first envisaged by Hydrocoop (Lempérière and Ouamane 2003). Electricité de France built the first PKW in 2006 at the Goulours dam (Figure 2.1) in France (Laugier 2007).



(a)

(b)

**Figure 2. 1** (a) The PKW system at the EDF Goulours dam in France. (Author and source: Frederic Laugier, EDF) (b) Upstream view of PKW at Goulours Dam, France during construction (courtesy of M. Leite Ribeiro)

*Sawra Kuddu PKW project, India*

It has been carried for the first time in India. The new technology in the form of the Piano- Key Weir (PK Weir) type of barrage has been designed and developed by IIT Roorkee, India (Figure 2.2). This is a hydroelectric project (111 MW), a run of the river project being constructed on river Pabber, a tributary of river Yamuna in Shimla District. The project comprises a Piano Key Weir of design discharge of 5240 m<sup>3</sup>/s. After seven years of delay, the Sawra Kuddu project will start power generation by April 2021 (Source “The Tribune” dated 22 Feb 2020.)



**Figure 2. 2** Swaraa-Kuddu Hydroelectric Project Thana, Solan, HP (Source Innovante Water Solutions Pvt. Ltd & Dr. Nayan Sharma)

Dam rehabilitation studies have also been carried out for PKW, which can be inferred from Literature (Bieri et al. 2009; Da Singhal and Sharma 2011; Machiels et al. 2010; Ribeiro et al. 2007).

Today more than 25 PKWs are in operation or under construction all over the world. A few of the PKWs are mentioned as below:

### ***Piano Key Weir in France***

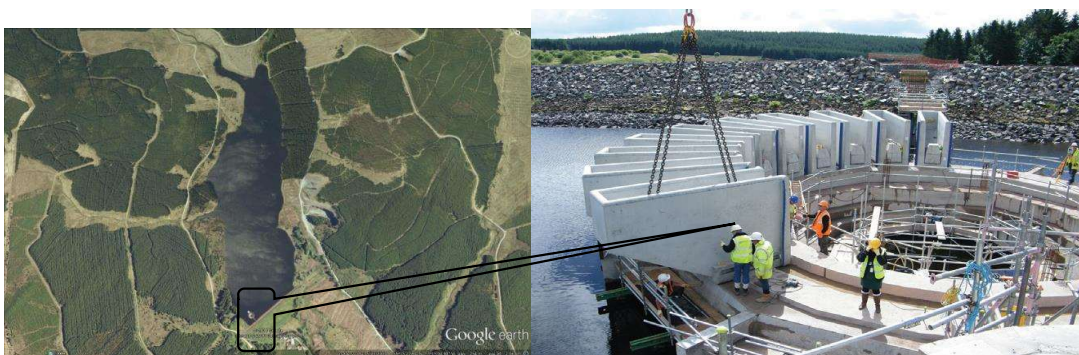
Piano Key Weirs have been widely used in France in the field (Figure 2.3). Saint-Marc Dam, Raviege Dam, Goulours Dam, Etroit Dam, Gloriettes Dam etc., are some examples. Design discharge of the weirs varies from 90 to 400 m<sup>3</sup>/s.



**Figure 2. 3** Spatial location of Saint-Marc and Raviege Dam PKW

***Black Esk Reservoir Dam in Scotland***

The new piano-key weirs are designed to pass the design flood (the PMF) of 183 m<sup>3</sup>/s with a flood surcharge of 0.97 m, saving the raising of the dam by about 0.7 m that would have been required for the alternative scheme. The simple raising of the weir around the bell-mouth rim (raising the height of a reservoir and bell-mouth Spillway) required innovative thinking for a world’s first by William Ancell (Figure 2.4).



**Figure 2. 4** Elevated views of the weir from the valve tower and spatial location of PKW (Courtesy of Scottish Water and Google Earth)

***Tzaneen Dam PKW in South Africa***

The PKW alternative is favored because it only requires a 2.8 m removal of the current ogee crest compared to a 7.5 m removal of the current ogee crest for the labyrinth weir. The hydraulic capacity of the modified PKW allows a safe passing of the SEF (4120 m<sup>3</sup>/s) in conjunction with a 1 m raising of the earth-fill embankments (Figure 2.5). This

design meets the requirements of all the constraints, such as limited spillway length as well as the limited high flood line constraints, which are part of the design criteria. PKW structures can be very efficiently used as permanent facilities to raise existing dams in a manner that reduces operational risks and the cost of stability-enhancing measures that may be necessary.



**Figure 2. 5** Spatial Location of Tzaneen Dam PKW (Ref: Google Earth)

### ***Loombah Dam PKW in Australia***

Following major flooding in 1993, when the dam came within a few hundred millimeters of overtopping, the embankment was raised with a parapet wall to provide additional flood storage. In the early 2000s, the flood capacity was again reviewed with updated hydrology and consequent assessments and the spillway capacity was found to be inadequate. An option study was commissioned to identify the preferred spillway upgrade, which identified an auxiliary spillway option through the left abutment, given the difficulty of widening the existing Spillway. This option was selected based on very limited geotechnical data. During the excavation works, it was found that the rock was extremely hard, and with no blasting allowed adjacent to the dam, excavation proved to be very slow and expensive. Following discussions with the contractor and designer, alternate spillway arrangements were considered, which required a reduced quantity of excavation (Figure 2.6). The final arrangement adopted and constructed was

a Piano Key Spillway designed for a 1 in 10,000 (years) Average Recurrence Interval.



**Figure 2. 6** Spatial Location of Loombah Dam (Australia) PKW (Ref: Google Earth)

### ***Van Phong Dam PKW in Vietnam***

The PK Weirs were selected as part of the project design as they can spill a significant discharge for a low nappe depth, which fits the site constraint of there being low allowable upstream water level, and this combination is safer and cheaper than solutions with either all gates or flaps gates. Design discharge intensity for the Piano Key weir has been taken as  $28.9 \text{ m}^3/\text{s}/\text{m}$  (Figure 2.7) (Chi Hien et al. 2006; Ho Ta Khanh 2012; Khanh 2004; Khanh 2017).



**Figure 2. 7** Under construction and constructed PKW at Van Phong Dam (Vietnam)

### ***Giritale Reservoir PKW in Sri Lanka***

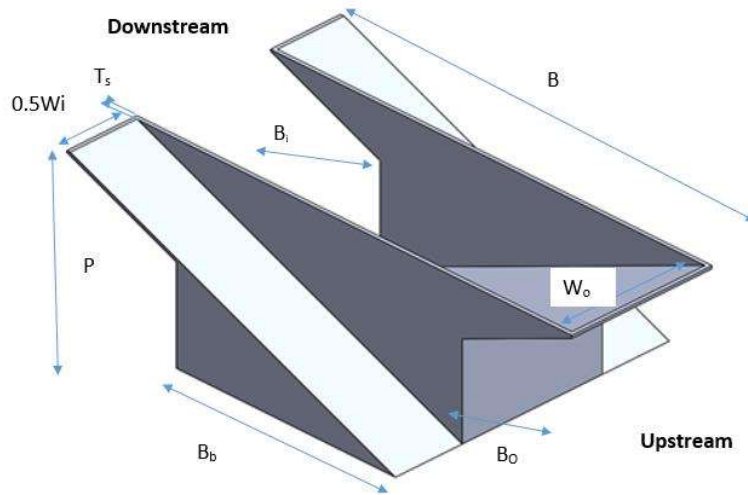
The Piano Key (PK) spillway constructed at Giritale in 2013 is the first of its kind in Sri Lanka (Figure 2.8). A capacity enhancement of the Giritale reservoir was required to overcome the frequent water shortages during cropping seasons and droughts. A decision was taken to enhance the capacity by increasing the crest level of

the Spillway, and a new spillway of the PK type was introduced to satisfy this requirement (Badr and Mowla 2015; Jayatillake and Perera 2013).



**Figure 2. 8** PKW at Giritale Reservoir

Design guidelines for PKW, based on field experience in different countries, has been accounted for by various authors (e.g., Vietnamese PKW (Chi Hien et al. 2006; Ho Ta Khanh 2012), French PKW (Bieri et al. 2009; Cicéro et al. 2010; Laugier et al. 2009; Ribeiro et al. 2007), in Belgium (Epicum et al. 2011b; Machiels et al. 2011a; Machiels et al. 2010; Machiels et al. 2014), in the USA (Anderson and Tullis 2012b; Anderson and Tullis 2012c), in Sri Lanka (Jayatillake and Perera 2013), in Switzerland (Pralong et al. 2011) and in India (Sharma et al. 2012; Ujeniya and Mehta 2015). The geometric features of PKW allow for greater crest length and make it a viable solution for not only increasing discharge capacity at existing and new waterworks but also providing more safety to hydraulic structures. A naming convention was formulated for a basic unit of PKW, which consisted of two half inlets and one outlet by Pralong et al. (2011), as shown in Fig. 2.9. The study on overhangs, the width of the sidewalls and inlet-outlet, slope and weir height has led to forming a basic understanding of the behavior of this weir.

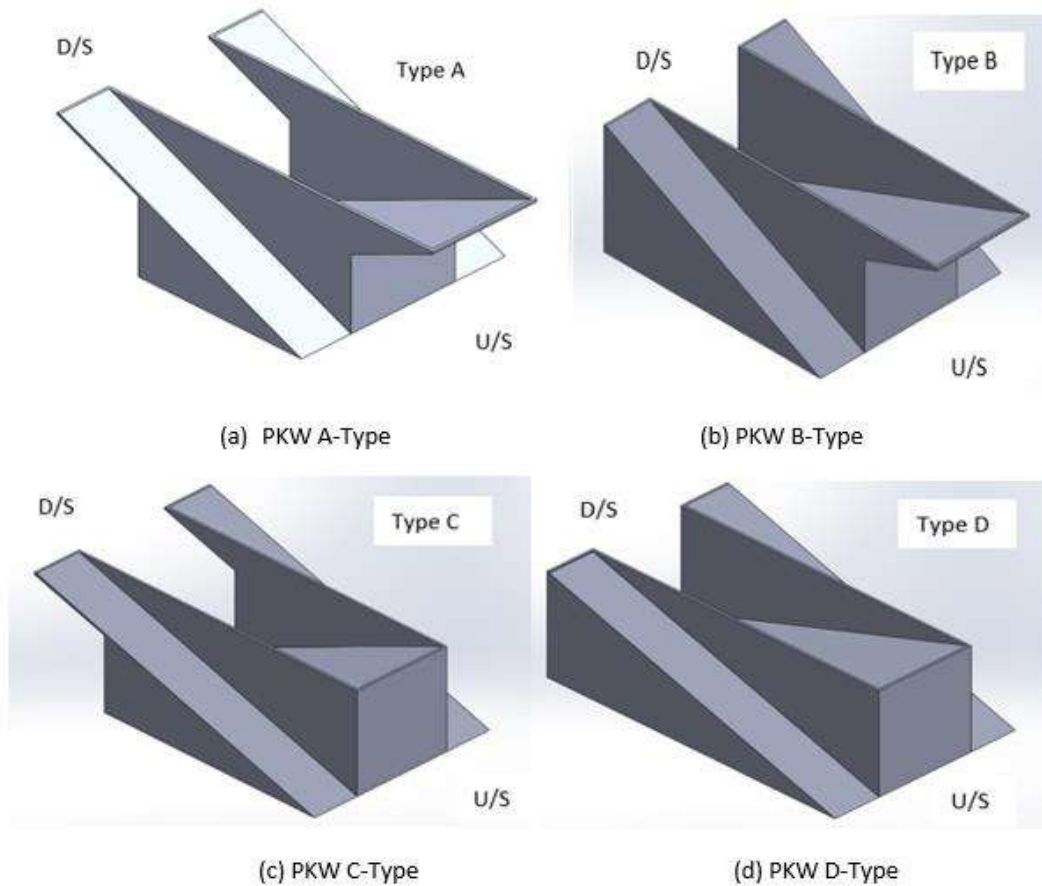


**Figure 2. 9** Fundamental parameters of a Piano key weir

The main geometric features of the Piano Key Weir consist of the total developed length  $L$  of weir, weir height, channel width  $W$ , the transverse weir crest length  $B$ , the total upstream and downstream cantilever (overhang) lengths  $B_o$  and  $B_i$ , and the upstream and downstream widths  $W_o$  and  $W_i$ . The geometry of PKW is such that it can easily be placed on top of an existing hydraulic structure while overhangs allow it to increase the crest length and thus increase its discharge capacity. According to PKW apices having overhangs, they have been further classified into four types (Fig. 2.10): (a) Type A: Symmetrical cantilevered overhangs (b) Type B: Upstream overhangs only (c) Type C: Downstream overhangs only (d) Type D: No overhangs.

Apart from its economic consideration for high flows, the traditional labyrinth solution cannot be used on top of the usual concrete gravity dam sections due to its flat bottom area requiring more space. The Piano Key Weir is an improvement over rectangular Labyrinth type weir, which has cantilevered apices so that the allowable weir developed length can be fit in the previous spillway channel width (Anderson and Tullis 2012b). The use of cantilevered apices enables improved hydraulic capacity while reducing the structural footprint (Lempérière and Ouamane 2003; Lempérière et al.

2011; Ouamane and Lempérière 2006).



**Figure 2. 10** Different Types of PKW

The geometric feature of Piano Key Weir enables it to be more easily adaptable than a Labyrinth weir for direct placement on dam crest (Pralong et al. 2011). Labyrinth weir is, therefore, less popular and find uses only in one per thousand large dams (Lempérière and Ouamane 2003).

## 2.2 Structural Integrity

Piano key weirs are themselves extremely hyper-static structures that are solid and very simple (Sharma and Tiwari 2013). They have a specific flow range varying from 3 to 1000  $\text{m}^3/\text{s}/\text{m}$ . Overall stability and anchorage of PKW have been studied for like Goulors dam, Gloriettes dam, Raviege dam and Saint-Marc (Bieri et al. 2010; Bieri et

al. 2011; Erpicum et al. 2011b; Laugier et al. 2009; Ribeiro et al. 2007; Vermeulen et al. 2011), in Malarce dam (Cicéro et al. 2010), upgrading of Dartmouth dam(Phillips and Lesleighter 2013), Hazelmere dam and Tzaneen dam in South Africa (Botha et al. 2013), Charmines dam(Valley and Blancher 2017) etc. The detailed report on the erection of PKWs has established them to be structurally safe, and load analysis can be done just like a gravity dam. Fuse devices have also been studied in association with PKW. Fuse devices are spillway structures that open only once and then are lost or permanently displaced. Such devices may be very cost-effective, delivering the benefits of a gated spillway with lower material and construction costs. Labyrinth fuse gates have been used in over 55 dams around the world (Le Blanc et al. 2011). Optimization of fuse gates can lead to economical and versatile solutions for flood routing of common floods. Lempérière et al. (2011) have suggested that the PKW solution is the best solution for discharges up to 5000 m<sup>3</sup>/s. For higher discharges, PKW, in association with fuse plugs, can give interesting and cost-effective solutions (Ouamane et al. 2017). The primary drawback of using Fuse plugs is the cost of replacement and lost reservoir storage if the fuse device does deploy. Typically, these types of spillways are used for floods having an annual probability of 1 in 100 or less. Concrete fuse plugs are relatively inexpensive to build, but they require a large amount of space. Further problems persist as to their long-term reliability (in particular, changes over time in the cohesion and compaction of the earth) and the downstream consequences of their deployment. Structural costs of Fuse plugs, though being lower, the complex design and hard currency required for patents are more difficult than a PKW. Moreover, operators are reluctant to use fuse gates because of costing and negative public image in case of gate loss.

## 2.3 Discharge Capacity of Piano Key Weir and its Comparison with Other

### Alternatives

A standard guideline for the hydraulic design of PKW is not available in the Literature. This is attributed to a limited understanding of the influence of more than twenty geometrical parameters (Sharma and Tiwari 2013; Tiwari and Sharma 2017b) on the head-discharge relationship (Anderson 2011). The head-discharge relationship of PKW has been obtained in the Literature by lumping the influencing geometrical parameters in certain groups by the use of dimension analysis.

The total discharge from a PKW is a function depending on many parameters, which are summarized as under:

$$Q = f(\rho, g, \nu, \sigma, \alpha, H, L, P, W, W_i, W_o, B_i, B, B_o, T_s) \quad (2.1)$$

where the fluid is characterized by its density  $\rho$ , the kinematic viscosity  $\nu$ , and the surface tension  $\sigma$ . The other parameters are related to the geometry of the PK-Weir: where  $L$  is the total developed crest length,  $P$  is the height of PKW,  $W$  = total width of PK-Weir,  $W_i$  and  $W_o$  are the widths of inlet and outlet keys, respectively,  $B$  is the total upstream-downstream length of PKW,  $B_i$  and  $B_o$  are the inlets and outlet key overhangs respectively,  $\alpha$  is the angle between inlet/outlet key crest and side weir of PK-Weir,  $T_s$  is the wall thickness,  $R$  is the radius of crest curvature,  $g$  is the acceleration due to gravity and  $H$  is the total upstream head.

By use of dimensional analysis, the discharge coefficient of PKW as a function of dimensionless parameters is written as

$$C_d = f\left(\frac{H}{P}, \frac{L}{W}, \frac{W_i}{W_o}, \frac{B}{P}, \frac{B_o}{B}, \frac{B_i}{B}, R, W_e\right) \quad (2.2)$$

Where  $R$  and  $W_e$  are the Reynolds and Weber number, respectively.

The efficiency of a PKW is often compared with a linear weir since, at higher heads, the efficiency of PKW reduces. It tends to behave like a linear weir, and hence the

increased discharge ratio is often expressed by ratio “r,” which is the ratio of the discharge through PKW ( $Q_{PKW}$ ) as compared to a linear weir with the same width  $W$  ( $Q_w$ ) (Ribeiro et al. 2007).

$$r = Q_{PKW}/Q_w \quad (2.3)$$

Extensive experiments from researchers led to finding the effect of each of the geometrical parameters on the discharge characteristics from a PKW.

Leite Ribeiro et al. (2011), to establish preliminary design criteria for PKW weirs, evaluated different results from 11 scaled models and found the developed length ratio ( $L/W$ ) to be the most crucial parameter of PKW. However, for a given value of  $H/P$ , the width of the inlet key ( $W_i$ ) becomes the most important parameter affecting the flow instead of  $L/W$ .

Ribeiro et al. (2013) compared the available data sets from different works of Literature under free-flow conditions. They found  $L$ ,  $W$ ,  $H$  and  $P$  to be the key parameters controlling the discharge through PKW. The authors further observed that the use of PKW for dam rehabilitation and new spillway projects has increased.

The use of vertical parapet walls placed on the crest of the PKW transforms its upper part into a rectangular labyrinth weir. The use of a parapet wall on the outlet key improves the streamlines of the approaching flow and therefore increases the discharge through outlet key volume and hence the total discharge capacity (Laugier et al. 2011).

PKW B type is the most efficient hydraulic option for new dams, while PKW A Type with inlet key larger than outlet key for existing dams. The increase of the downstream key width and the upstream weir overhang significantly increases the discharge coefficient  $C_d$ . The width of the inlet key 1.2 times than that of the outlet key results in a better hydraulic performance (Lempérière and Vigny 2011; Lempérière et al. 2011), while sidewall angle narrowing the inlet key and widening the outlet key as we go

downstream improves the discharge capacity (Schleiss 2011). The entrance shape under the upstream overhangs affects the hydraulic performance of the PK-Weir, with the rounded shape being significantly better than a flat one. Also, the optimal value of the developed length ratio(L/W) was suggested between 5 and 6 (Noui and Ouamane 2011). Laugier et al. (2011), by numerical modeling, showed that an increase in sidewall thickness (T<sub>s</sub>) at low heads resulted in the loss of discharging capacity.

The transition from a clinging nappe to leaping and then to a springing nappe flow was observed, and the flow behavior was found to be different at the upstream crest from lateral and downstream crest under the low head. For H/P between 0.09 and 0.1, the nappe on the lateral crest was free, while for  $0.16 \leq H/P \leq 0.17$  on the downstream crest of the inlet, the nappe is completely aerated. Under higher head control section is formed at the inlet leading to reduced effective weir crest length and hence reduced C<sub>d</sub> (Machiels et al. 2009; Machiels et al. 2011b).

After that, many experiments were done to ascertain the head-discharge relationship of a PKW on standard models and models with geometrical adaptations.

The head-discharge relationship for a “Standard model” of PKW with all the characteristics defined by only a single parameter ‘representative weir height, ‘P<sub>m</sub> was presented as

$$q = 4.3hP_m^{.5} \quad (2.4)$$

Where “h” is upstream head over the weir crest measured in meters within the range of 0.4 P<sub>m</sub> to 2 P<sub>m</sub>, and q is the specific weir discharge per unit width of spillway channel in cubic meters per second per meter of the weir (Khanh 2013).

Anderson and Tullis (2012a) also presented extensive experimental findings on the head-discharge relation of PKW and compared them to that of rectangular Labyrinth weirs with and without slope. Ribeiro et al. (2012) performed tests on sets of several

PKWs Type A and identified the primary and secondary parameters affecting the flow. They expressed head–discharge relation of PKW by providing an expression for increased discharge ratio( $r$ ) in terms of four correction factors  $w$ ,  $p$ ,  $b$  and  $a$ . The correction factors were due to  $W_i/W_o$ ,  $P_o/P_i$ ,  $(B_o+ B_i)/B$  and  $R_o/P_o$ , respectively, where  $P_o$  is the height of outlet,  $P_i$  is the height of inlet of PKW and  $R_o$  is the height of the parapet wall on the outlet section of PKW.

$$r = 1 + 0.24 \delta (w * p * b * a) \quad (2.5)$$

Where

$$\delta = \left( \frac{(L-W)P_i}{WH} \right)^{0.9} \quad (2.6)$$

Kabiri-Samani and Javaheri (2012) conducted an extensive experiment (Fig. 2.11) both in free flow and submerged conditions to find the head-discharge relationship of a PKW.

They obtained the following relation for  $C_d$ , expressed as a function of non-dimensional groups of influencing geometrical factors of PKW:

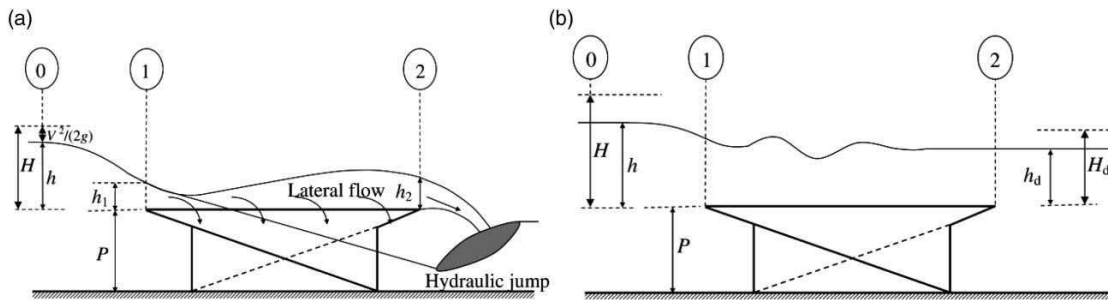
$$C_d = 0.212 \left( \frac{H}{P} \right)^{-0.675} \left( \frac{L}{W} \right)^{0.377} \left( \frac{W_i}{W_o} \right)^{0.426} \left( \frac{B}{P} \right)^{0.306} e^{(1.504 \left( \frac{B_o}{B} \right) + 0.093 \left( \frac{B_i}{B} \right))} + 0.606 \quad (2.7)$$

where  $g$  is the acceleration due to gravity.

Discharge can then be calculated from

$$Q = \frac{2}{3} C_d \sqrt{2g} L H^{1.5} \quad (2.8)$$

The above equation is valid under following conditions(1) $H > 30$  mm, (2) $0.1 \leq H/P \leq 0.6$ , (3) $2.5 \leq L/W \leq 7$ , (4) $1 \leq B/P \leq 2.5$ , (5) $0.33 \leq W_i/W_o \leq 1.22$ ,  $0 \leq B_i/B \leq 0.26$ , (7)  $0 \leq B_o/B \leq 0.26$  and (8) $H_d/H \leq 0.6$ . Submergence occurred when Submergence factor  $S$  ( $H_d/H$ ) was greater or equal to 0.6, and this reduces the coefficient of discharge  $C_d$ .



**Figure 2. 11** Hydraulic aspects over PKW flow for (a) free (b) submerged weir flow  
(adapted from Kabiri-Samani and Javaheri (2012))

(Oertel 2015) focused on comparing the discharge coefficient of PKW with geometrical additions at the downstream end of the top of the structure with the help of experimental and numerical models. The geometrical adaptations decrease the efficiency of PKW for low heads ( $H/P < 0.15$ ) as compared to PKW without any adaptations.

Khassaf and Al-Baghdadi (2015) presented the discharge capacity as a function of sidewall angle and sidewall inclination angle, which are  $\alpha$  and  $\beta$  respectively for non-linear PKW.

(Khassaf et al. 2016) performed experiments on Piano Key weir Type B to determine the effect of geometrical parameters on the discharge coefficient and derive an empirical formula for estimating the discharge coefficient of PKW type B for free-flow conditions.  $C_d$  was presented in an empirical relationship with different geometrical parameters of PKW B Type. The discharge capacity at low heads was also compared to a Creager weir and found to be 400 percent more for a given upstream head. Hu et al. (2018), by the use of numerical simulation, showed that under the low head condition, the side crest portion of PKW contributes to the main discharge from PKW, which is greatly decreased as the upstream head increases due to submerged flow conditions and nappe interference. An empirical relation for the contribution from individual keys in the discharge through PKW was suggested.

Khassaf and Al-Baghdadi (2018) did an extensive experimental investigation to analyze the behavior of piano key weir under submerged flow conditions. They concluded that the discharge reduction factor ( $C_s$ ) is mainly influenced by the submergence factor “S.” Discharge reduction factor ( $C_s$ ) is influenced negligibly by the parameters  $L/W$ ,  $B_i/B$ , and  $P_d/P$ , where  $P_d$  is the dam height.

The Head discharge relationship of PKW was compared with that of Creager weir in the experiments done by Tiwari and Sharma (2017a). The head over exponent was interestingly observed to be 0.75 for a developed length ratio ( $L/W$ ) equal to 4.76. Discharge Head relationship was observed as below:

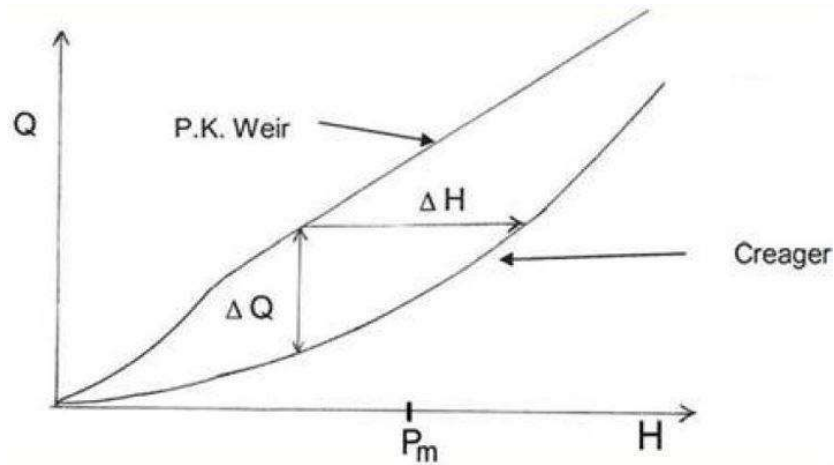
$$Q = CLWh^{3/4} \quad (2.9)$$

Where “ $h$ ” is head over the crest of PKW. The head to weir height ratio ( $H/P$ ) was kept below 0.1, and the head was also less than 30 mm.

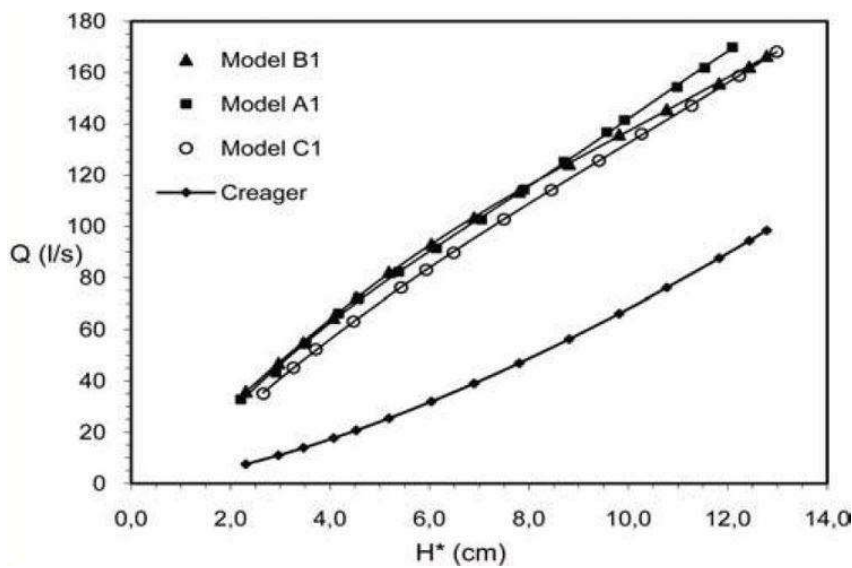
Lempérière et al. (2011) compared the hydraulic performance of a reference design of a Piano key weir with that of a Creiger weir (Fig. 2.12). The discharge increase  $\Delta Q$  was observed to be close to the discharge of a Creager weir overtopped by a nape depth equal to  $P_m$ , where  $P_m$  is the maximum wall height.

Piano key weir was also found to be an excellent alternative over Creager or Labyrinth weirs to increase the overflow discharge capacity of existing and new hydraulic structures (Leite Ribeiro et al. 2009; Leite Ribeiro et al. 2011).

(Ouamane 2011) have presented in studies of flow over three PKW with varying geometry and compared it to the Creager weir. In comparison with a Creager weir (Fig. 2.5) for low head flows ( $H/P < 0.2$ ), the discharge capacity of PKW is four times greater for models with upstream overhang (model A1 and B1) while 3.5 times greater than the model without upstream overhang (model C1) (Fig. 2.13). Even for greater heads ( $H/P > 0.45$ ), the performance is doubled.



**Figure 2. 12** Hydraulic performance of reference designs adapted from Lempérière et al. (2011)



**Figure 2. 13** Rating curves of the three different models A1, B1, C1 and comparison with a linear Creager (adapted from Ouamane (2011)).

Lempérière and Ouamane (2003) presented studies of both the hydraulic data and cost savings for Piano Type A Model for wall height  $H$  equal to 4 m and Piano Type B Model with a wall height of 8 m with that of a Creager weir along with an increase in live storage of the reservoir (Fig. 2.14). The reinforced concrete and ordinary concrete per meter length of Spillway required along with an increase in specific capacity and nappe depth saving have been compared extensively for PKW, Creager and traditional

labyrinth weir for their use in existing and new structures with or without gates and along with fuse plugs in the Literature.

The discharge coefficient of a rectangular labyrinth weir (RLW) with and without false ramped floors was also compared to PKW by experiments done by Anderson (2011), and PKW depicted higher Cd values for different values of H/P.

Hydraulic tests performed in various countries have shown that a Piano Key Weir can provide a discharge capacity about three times that of a typical rounded-crest weir. PKW of any type has a much greater discharge per unit width than an ogee crested weir (Fig. 2.15).

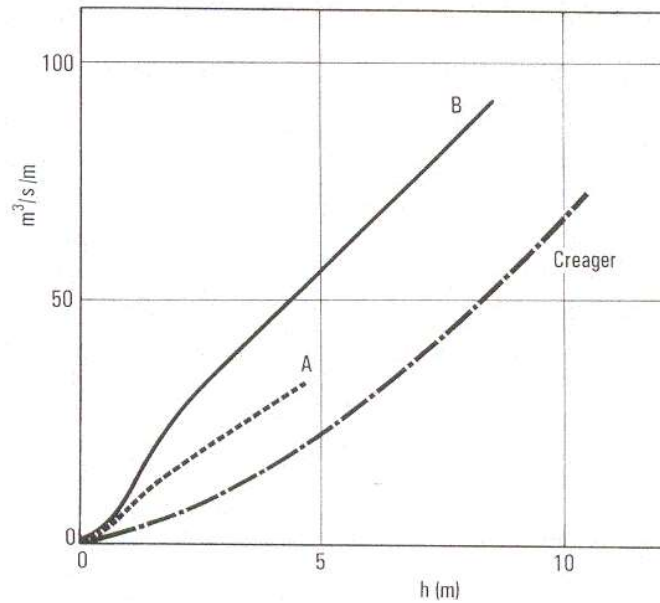
However, greater head in Piano Key Weir results in a smaller increase in efficiency when compared to a linear weir. PKW has been designed for a maximum H/P ratio lower than one where “P” is the height of the weir (Ribeiro et al. 2012) due to reduced effective development length due to outlet saturation.

PKW is 10% more efficient than a traditional labyrinth weir with the same crest print for a head H equal to its height  $P_i$ , as shown by Anderson and Tullis (2012a). The global discharge coefficient of a PK weir is found to be higher than a corresponding rectangular labyrinth or Trapezoidal labyrinth weirs (Anderson and Tullis 2012b; Blancher et al. 2011) and the gain of efficiency with a PK weir can reach 20%.

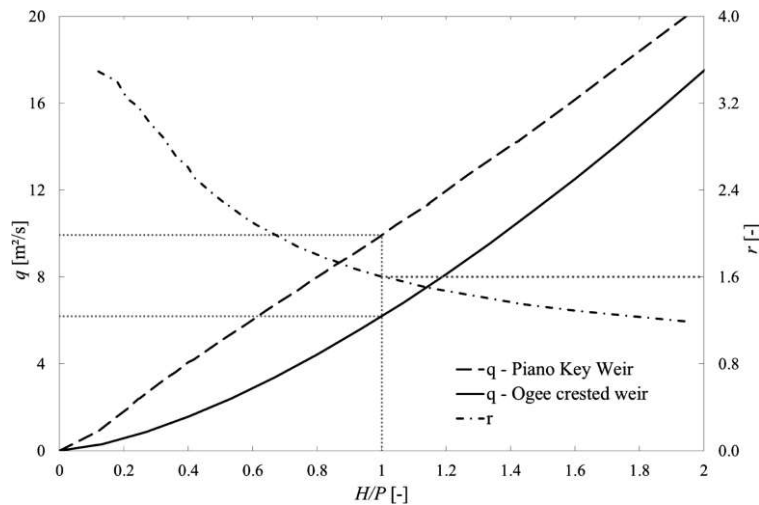
Erpicum et al. (2011b) carried out tests on various scale models with energy dissipater downstream of PKW along with a rehabilitation project focusing on the PKW design. Blancher et al. (2011) compared the discharge coefficients of a PKW with a labyrinth and Creager weirs and found the discharge coefficient of PKW to be substantially higher for the entire H/P ratio.

Paxson et al. (2013) also compared the hydraulic efficiency of PKW with that of a labyrinth weir and gated Spillway using examples. All the results in the experimental

works done by Tiwari and Sharma (2017) also showed the discharge from PKW to increase by four to five times, the discharge intensity higher for low heads and slowly reducing to the same Creager weir discharge for very high heads.



**Figure 2. 14** Hydraulic data and saving of PKW "A" and PKW "B"(adapted from Lempérière and Ouamane (2003).



**Figure 2. 15** Discharge per unit width  $q$  of a PKW compared to an ogee crested weir

– PKW:  $P = P_i = P_o = 2\text{m}$  and  $L/W = 5$ ; Ogee crested weir: design head=2m, CS

=0.494(adapted from Erpicum et al. (2013)

The labyrinth weir and Piano key weir have been progressively tested by varying their plan or sill geometry to incorporate higher discharge capabilities.

An experimental study has been conducted for ascertaining the hydraulic performance of Trapezoidal Piano key weirs, with the study suggesting a 22% increase in the discharge capacity (Mehboudi et al. 2016).

Arced Labyrinth and Piano key weirs have also become a subject of recent experiments in this regard. Monjezi et al. (2018) studied the hydraulic performance of arced labyrinth weirs and concluded that the arced shape resulted in improved efficiency of both linear arced weir and labyrinth arced weir up to 21% and 57%, respectively. Chahartaghi et al. (2019) conducted experiments on eight PKW models with four of them featuring internal arced angles of 90, 65, 50 and 45 degrees, respectively, with a trapezoidal plan along with their numerical study using FLOW 3D software. The results of the hydraulic performance of these Arced Trapezoidal PKWs (ATPKWs) were then compared to the results with linear rectangular PKWs. The study suggested that Linear rectangular PKWs (LRPKWs) exhibited better performance at a lower  $h/p$  ratio. Increasing the  $h/p$  ratio led to consistent improvement in the performance of ATPKW. Further decreasing the internal Arc angle initially reduced but later greatly augmented the hydraulic performance of ATPKW.

Guo et al. (2019) also analyzed the different empirical formulas from literature along with their limitations. They then proposed a new formula that integrates the existing data with the results from dimensional analysis and multiparameter optimization. All these formulas were refined for an A-Type PKW.

The notable empirical formulas for getting discharge capacity from PKW have also been compared by Kumar et al. (2019). They have categorized the empirical formula with the  $H/P$  ratio to see which empirical equation is best suited for the various ranges

of  $H/P$ , where  $H$  is the total head upstream of PKW and  $P$  is the height of PKW.

#### **2.4 Economic Aspects**

The association of a PKW with existing dams requires specific cost study as unit cost is higher for new dams. The key economic parameters are the saving in nappe depth  $\Delta H$  or the increase  $\Delta Q$  in specific flow  $Q$  as compared with a Creager weir. Lempérière and Vigny (2011) have presented a cost comparison of PKW with Creager Sill on Gravity dam. The relative quantity of both Reinforced concrete and Ordinary concrete is about one third for a height of PKW of 2 meters, while it is further reduced to one fifth for a height of PKW of six meters as per their study. For the reference designs A and B, the saving  $\Delta H$  in depth is close to  $0.5 \times P_w$ , where  $P_w$  is the maximum wall height of the PKW for usual nape depths.

The volume of reinforced concrete is about half the volume of traditional labyrinths for the same saving. PKW requires about  $0.5 \text{ m}^3$  of reinforced concrete and saves  $1 \text{ m}^3$  of ordinary concrete to earn  $1 \text{ m}^3/\text{s}$  of extra discharge compared to a Creager sill. PKW requires 3 to  $5 \text{ m}^3$  of reinforced concrete and saves 5 to  $10 \text{ m}^3$  of ordinary concrete to earn one meter of the upstream head along one meter of the Spillway.

Lempérière and Ouamane (2003) have presented the length of spillway requirement in their work suggesting the use of PKW to both improve the live storage and as an effective spillway. The cost of construction and cost efficiency have been discussed in detail and the costs compared with that of gated spillways and fuse gates.

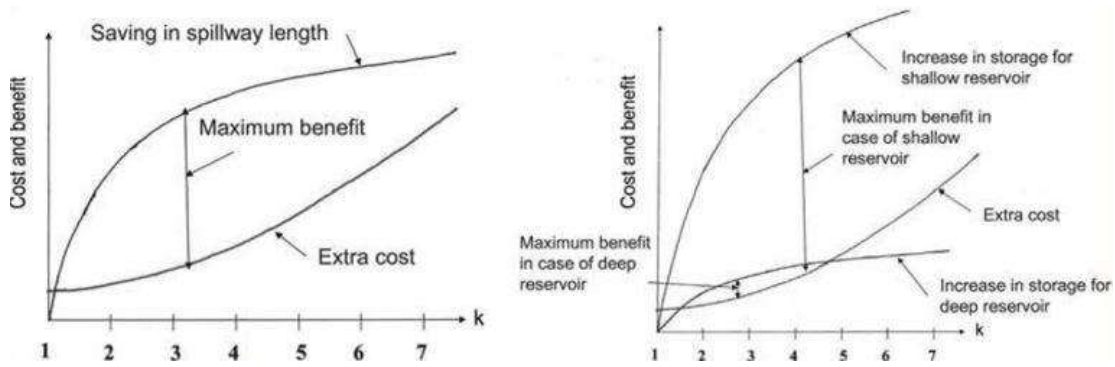
It has been suggested to use PKW than fuse plug for new dams. However, fuse devices find interesting uses for improving already constructed large spillways and some dams, as in Arch dams, where PKW placements are difficult on top of the dam or lack of technical expertise, particularly in developing countries. Fuse plugs are less attractive for increasing the storage of the reservoir or in new dams or where the increase in a

reservoir level is more than one meter. Fuse plugs require about  $0.5 \text{ m}^3$  of ordinary concrete to increase the flow by one  $\text{m}^3/\text{s}$  (Lempérière and Ouamane 2003).

The solution without downstream overhang offers a significant saving (about 10%) over symmetric overhangs, and structural efforts are less significant for large specific discharges. So, this could be the most attractive choice for several future large dams (Ouamane 2011).

A Piano Key Weir can be made of reinforced concrete or steel, although the practical height limit for a steel weir is 2 to 3 meters. The weir can be built on-site, or it can be partially or entirely prefabricated. One cubic meter of reinforced concrete can increase the discharge capacity by more than two centimeters. Therefore, the cost per unit discharge is quite low, especially in regions where labor and reinforced concrete costs are low. The Piano Key Weir at Electricité de France's Goulours Dam increases the spillway discharge capacity by a factor of four over a conventional spillway.

The "k" value, which is the ratio of discharge coefficient of the PKW as compared to the discharge coefficient of a Creager sill for an equal upstream water head, is taken on whether we are trying to increase the discharge or the storage. The savings (benefits) and the optimal "k" value have been presented in this study (Lempérière and Vigny 2011). They also presented detailed comments on cost and economy (Fig. 2.16). The cost per meter of the PKW dam in the run-of-the-river scheme is around 20% of the cost per meter of a gated dam, even with a length two or three-fold the length of the gated dam. PKW may thus reduce by half the cost of many run-of-river dams.



**Figure 2. 16** Economical optimizations with constant water level (left) and constant spillway length (right) (adapted from Lempérière and Vigny (2011)).

PKW is also more cost-effective than a Trapezoidal Labyrinth weir, which has double the specific flow from a traditional Creager weir. In terms of construction material required, Labyrinth weirs require one or two cubic meters of reinforced concrete per cubic meter of flow increase. In contrast, the use of PK weirs can result in considerable economic savings. The volume of reinforced concrete is half the volume of traditional labyrinth weir for the same saving in nappe depth for the reference designs of (Lempérière and Vigny 2011). Another detailed study by Ouamane (2011) on the use of PKW suggests a big cost reduction for the majority of new dams and a guarantee of safety along with a possible increase of many existing reservoir storages.

Paxson et al. (2013) have compared the cost between a 2-cycle labyrinth weir with a  $15^\circ$  sidewall angle ( $\alpha$ ) with a 4-key PKW with similar head-discharge characteristics to allow for a better understanding of cost incurred. PKW with similar head-discharge characteristics to the labyrinth weir requires 35% less concrete volume, primarily due to the significantly reduced upstream to the downstream footprint of both the foundation and weir. They also compared the cost of a PKW with a gated spillway to pass the same design discharge. They found that the application of a gated spillway would be significantly more costly than a PKW, primarily due to the cost to furnish and install the gates. However, since each project presents its own set of opportunities and

constraints, the applicability for a particular spillway type should be evaluated on a site-by-site basis. Flap gates are generally more expensive (40% more) besides the danger of the phenomenon of resonating with the flow. At the same time, PKW offers the cheapest solutions, with their cost only a small part of the total project cost (Vermeulen et al. 2011). The fuse devices, however, can result in the loss of some elements and water, for instance, once per century. The use of PKW for one half of a spillway and fuse plugs or fuse gates (which only tilts for a flood with low probability) for the other half presents an interesting solution (Sharma et al. 2012). PKW, in association with fuse plugs, has also been studied and offers a new solution for the effective dissipation of discharge downstream by Ouamane et al. (2017).

## **2.5 PKW Aeration**

In terms of aeration requirement also, it has been found that the flow over PKW is considerably aerated, thus significantly reducing the risk of cavitation or downstream erosion in different model tests as well as existing labyrinth-shaped spillways by different researchers. It is not clear whether these aeration systems are essential for PKW, as physical models seem to show that flow is naturally aerated and rather stable. Lodomez et al. (2017) carried out their study to investigate the risk of nappe oscillation occurrence on Piano Key weirs by using two complementary methods, i.e., an images analysis and a sound analysis. The influence of weir width and the effect of an inclined apron downstream of the chute have been considered. Experiments were performed on various crest width and chute length configurations. They were tested on a prototype-scale linear weir with a quarter-round crest shape that approximates the sidewall of a piano key weir. A free-falling nappe causes air friction. If an air pocket is “trapped” between the nappe and the structure, this pocket will then depress, leading to nappe beats reducing the discharge and potentially causing damage (resonance phenomenon).

This problem is well known on the tilting gates or front or labyrinth weirs. The risk of vibration, however, seems less critical for the hyperstatic structure that is a PKW. The study shows that nappe oscillations are unlikely to occur on PKW, thanks to their specific geometric features, while they should occur on a labyrinth weir of the same crest print.

PKW has an advantage compared to a traditional vertical labyrinth, whereby the installation of aeration pipes might be complex.

The earlier average airflow rate in the order of 5 to 10% of the water flow was taken for the aeration design of spillways, which was considered highly conservative. Vermeulen, Vermeulen et al. (2017) have given a new air demand estimation method based on the work of Ervine and Elsayy (1975) on air driven by a rectangular jet falling into a volume of water in the open (Falvey 1980). This new estimation method has been recently validated by measures of air demand on Malarce dam PKW while overflowing. The new PKW aeration network design method significantly reduces the diameter of the pipes, which facilitates their implementation and their integration into the PKW base. For a PKW, airflow carried by jets coming from inlet or sidewalls may be considered. The new empirical formula which predicts the amount of air in a jet  $Q_{air}$  (m<sup>3</sup>/s) as

$$Q_{air} = (q_w L_n) 0.26 \left( \frac{L_n}{P_n} \right) \left( \frac{d_j}{h_n} \right)^{0.446} \left( 1 - \frac{V_m}{V_i} \right) \quad (2.10)$$

where  $q_w$  is linear water flow overflowing inlets or sidewalls (m<sup>3</sup>/s),  $L_n$  is nappe width (m),  $h_n$  is the nappe thickness (m),  $P_n$  is nappe perimeter which is assumed as  $P_n = 2 * (h_n + L_n)$ (m),  $d_n$  is the falling jet height (m),  $V_i$  is the jet speed at impact (m/s), and  $V_m$  is the minimum velocity required to entrain air (1.1 m/s according to authors).

The preliminary results on the Malarce dam suggest a linear relationship for aeration flow between air discharge and hydraulic head. The air demand is equivalent to 1.4%

of the water discharge rate, which is much lower than the rate for which it was designed ( $10\text{m}^3/\text{s}$ ) (Ouamane et al. 2017).

Though the thin-walled nature of PKWs is advantageous from a hydraulic perspective, it weakens the structure from vibration due to the relatively low frequency of thin walls, which could cause resonance leading to fatigue failure. Flow over PKW at the inlet crest, at small heads, tend to form an enclosed pocket of air underneath a nappe, which, when not aerated, becomes sub-atmospheric. The resonance behavior caused by the upstream separation bubble and the vortices shed from it may be occurring, and only a local disturbance of the flow at this corner nappe causes the oscillations to cease. At higher heads, the air pocket along the transverse wall transforms into a bubble suspended between the wall and the nappe, which is highly unstable and oscillates upstream and downstream along the wall (Denys et al. 2017). It is difficult to determine the clear and reasonable design criterion for the aeration device and requirements because the scale effects are not similar for air and water actions, and vibrations could appear for a specific range of discharge floods. The engineering processing of available data is still ongoing, which may lead to a real optimization of aeration systems for Piano Key Weir.

## **2.6 Sediment Erosion and Transport Aspect**

Free flow weirs are hydraulic structures that allow water to flow over them while impounding the water upstream. The waterways of hydraulic structures like barrages are often larger than required due to the overestimation of the design flood. The barrage gates are not completely opened except during the passage of the design flood, causing deposition of sediments and formation of shoals in the reservoir behind. (MISHRA and SEN 2011). The issue of sediment passage is necessary to avoid upstream inundation as well as to maintain a navigable waterway. It can be achieved by either flushing the

sediment or carrying them over the weir crest. Abutments, Bridge piers and the downstream of hydraulic structures like barrages & spillways are subjected to scouring and have also been studied to understand the scouring mechanism (Ayoubloo et al. 2011; Azamathulla and Zakaria 2007; Beheshti 2015; Beheshti 2016; Ghosh et al. 2009; Goel 2009; Jamieson et al. 2011; Mohammadpour et al. 2013; Najafzadeh et al. 2013; Najafzadeh and Lim 2015; Pandey et al. 2020).

Sediment carrying characteristics of a weir has long been studied to know about the self-cleaning capacity of weirs as it plays a pivotal role in ascertaining the life of the reservoir created by impounding water upstream of the weir. Self-cleaning capability requires the necessary turbulence near upstream of weirs. Turbulence studies have been carried out in alluvial channels (Barman et al. 2018; Kumar and Rao 2010; Tiwari and Sharma 2016), curvilinear channels (Sharma and Kumar 2016) and wall-bounded flows (Karimpour and Venayagamoorthy 2014; Karimpour and Venayagamoorthy 2013; Karimpour and Venayagamoorthy 2015) by various authors.

Rectangular weirs both impound the water and are not able to effectively provide a passage for sediment over the weir crest due to less velocity and turbulence upstream of the weir. Since more types of weirs subsequently were undertaken for a study showing higher discharge capacity, it becomes imperative to study their sediment carrying capabilities.

A more hydraulically efficient weir, “Labyrinth weirs,” was also examined for their self-cleaning process. Experiments were done on rectangular and trapezoidal labyrinth weirs with four types of sediment under different flow conditions by Gebhardt et al. (2018). Froude number remained the dominant parameter affecting the scouring mechanism. The study also revealed that the process of self-cleaning for the rectangular plan began at a lower discharge compared to the trapezoidal plan. The study suggested

that self-cleaning can be expected with Labyrinth weirs.

A more hydraulically efficient weir, “Piano Key Weir,” was further studied for its sediment erosion and transportation capabilities.

Sharma and Tiwari (2013) showed that as the flow approaches the PKW, the upward velocity (Z component) in the lower level increases, which leads to uplift force generation. This Z component of velocity is quite significant even for low flows of 0.031 cumec discharge to flush the sediment over the PKW.

Jüstrich et al. (2016) studied the scour formation and corresponding ridge generation downstream of Piano Key Weir. A physical model of PKW was set up in a channel, and the sediment bed surface, particularly the scour hole and the ridge, were studied with a vertical laser fixed on an automatic trolley. A prediction model for the scour dimensions, and maximum ridge height was presented in the literature. The study revealed that the maximum scour-hole sizes depend on the sediment characteristics, discharge, head difference and tailwater depth. In contrast, the maximum ridge height is dominated by the incipient sediment transport conditions along its top. The scour depth at the downstream of PKW foundation  $Z_P$  was presented as a function of the maximum scour depth  $Z_{SM}$  as

$$\frac{Z_P}{Z_{SM}} \cong 0.36 \quad (2.11)$$

With all the scour profiles normalized with  $Z_{SM}$ .

The study of the upstream erosion and sediment passage by PKW was studied by Nosedá et al. (2019) on three physical PKW models with two sediment granulometry and each with six discharges. The study of erosion data with time revealed the self-cleaning capability of PKW with 88% removal just after two hours of flow with releases varying from 0.015 to 0.045 m<sup>3</sup>/s. Modified rating curves were presented due to high upstream sediment levels with discharges ranging from 0.005 to 0.1 m<sup>3</sup>/s, and data were

compared both for reservoir and channel approaches from earlier literature. The study of sediment passage and sediment transport revealed PKWs are far better at self-cleaning than labyrinth weirs. Lean inlet keys were observed for densimetric Froude number  $F_d$  greater than 2.7 for PKWs, while the same was observed at  $F_d$  greater than 5 for labyrinth weir inlet key. The maximum local front scour depth ( $s$ ) in terms of  $F_d$  was normalized with the PKW height ( $P$ ) and presented as:

$$\sqrt{\frac{|s|}{P}} \left( \frac{h_c}{d_{50}} \right) = 160(F_d - 2.5) \quad (2.12)$$

For  $2.5 \leq F_d \leq 3.5$

where  $h_c$  is the upstream critical head and  $d_{50}$  is the median particle size.

The experiment pointed out that a fixed bed inhibits the creation of local upstream local front scour while a mobile bed allows its generation.

Kumar et al. (2021a) studied the discharge characteristics of Piano Key Weirs with and without upstream siltation with Type-A PKW models with noses below the upstream apices. They suggested that the upstream siltation had no impact on the discharge efficiency of submerged PKW but observed a maximum reduction of 4% under free-flow conditions. They even proposed equations for free-flowing PKWs with errors well within permissible limits.

Kumar et al. (2021b) further investigated the mechanics of movement of singular quartz gravel and coarse riverbed particles upstream and over the inlet key of three Type-A PKWs. Rolling and saltation regimes were observed over the key, and the CFD simulations showed a rapid increase in shear stress at the key end.

Kumar and Ahmad (2020) conducted an experimental investigation on a three-cycle PKW to study the scour pattern downstream of inlet and outlet keys with and without a solid apron. The study suggested that falling and impringing jets originating from inlet and outlet keys were liable for the formation of dip and ridge downstream. Scour

formation was negligible for high submergence downstream, and the presence of a solid apron downstream led to a significant reduction in scour.

Pfister et al. (2013) studied the debris-blocking sensitivity of three PKW configurations for reservoir-type approach flow. They concluded that the dimensionless parameter  $D/H$ , where  $D$  is the trunk diameter of debris and  $H$  is the total approach flow head, is the dominant parameter indicating whether the debris will be trapped or pass over PKW. The blockage probability was 100% when  $D/H$  was greater than 1.0, while all trunks passed when  $D/H$  was less than 0.3.

## **2.7 Field Applicability**

PKW is convenient for most concrete and earth dams, which are already equipped with a free flow spillway (Ouamane and Lempérière 2006). PKW has been found suitable as a free flow spillway for new dams, for providing additional free-flow spillways for gated spillways or up-gradation of existing free flow spillway by combining with existing spillway or fuse devices as discussed earlier. PKWs have also been used to replace radial gates on barrages over large rivers like Van Phong and Xuan Minh (Khanh 2017). The use of PKW as a side weir also shows higher discharge capacity than conventional side weirs (Karimi et al. 2017; Karimi et al. 2018), which can be effectively used in channel applications. The use of PKW as an overflow device on a sedimentation basin for a wastewater treatment plant has also been studied (Ribi et al. 2017). PKWs have found use in numerous run-of-river schemes and also for use in irrigation canals or sewage tunnels (Lempérière et al. 2011).

## **2.8 Scope of Future Work**

There has been much research concerning PKW, obtained by several experimental results and by constructing PKWs around the world. However, more in-depth insight is still required in some topics to address the issues concerning them adequately.

Experiments with changing sill geometry and plan are continuously performed to get higher discharge capability and are under study. Although few authors have addressed the risk of floating debris, it warrants further investigation. Experiments have been conducted with trunk roots; however, more research is needed if these schemes are located near catchment areas covered with forest or in inhabited areas.

The methods of construction need further study as prefabricated reinforced concrete can be an exciting solution. Cost and delays are the main issues affecting a project, and as such, methods for rapid construction of PKWs based on hydrologic data and a minimum number of parameters and local conditions could be further taken up for study.

Structural aspects, along with material selection used for PKW construction like composites, can be an area of further research. Associating PKWs to other types of spillways with minimum cost is an area of further inspection.

The use of numerical modeling to study or even replace the physical models, which are often more time-consuming and costly, can be exciting.

The dissipation of energy downstream is another issue concerning PKWs. Various energy dissipators and their combination can be further studied for effective energy dissipation with minimum cost.

## **2.9 Summary and Conclusions**

Piano Key Weir is a free flow weir, which has started gaining popularity around the world for both existing as well as new dams and spillways. PKW is characterized by a simple geometry that comprises the use of reinforced cement concrete at-site or prefabricated units, which can be structurally placed on top of dams. They are free-surface weirs with a specific flow 2 to 4 times the standard linear weir and thus increasing the discharging capacity of both existing and new dams. PKW is being used

in combination with existing spillway structures for improving their spillway capacity. They are being used for run-of-the-river schemes for increasing the storage of many existing reservoirs, increasing the spillway capacity to reduce dam risk failures with the use of about 0.5 m<sup>3</sup> of reinforced concrete for each further increase of 1 m<sup>3</sup>/s depending on site conditions. They have lesser aeration requirements and reduce the risk of dam overtopping. They are structurally stable, economical and offer broad field applicability. Turbulence generated near the upstream of these weirs provides self-cleaning characteristics to these weirs. The installation of PKW around the world has presented a general design subject to the conditions of their construction. Although few topics demand future scope of work, altogether, Piano Key Weir offers an excellent alternative for Dam rehabilitation in comparison to its counterparts.

\*\*\*\*\*