Study of flow over piano key weir of different plan shapes with free and partially submerged outlet conditions

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ABSTRACT

Piano key weirs are being increasingly used for better flood passage downstream, both as a new structure or on top of hydraulic structures like a dam, to increase their discharging capacity as well as reservoir storage. Much research has been done on rectangular plan-form, while other plan-forms warrant attention. The present study focuses on two different plan geometries of PKW, i.e., rectangular (RPKW) and trapezoidal with angle α equal to 9 degrees (TPKW9) for their head-discharge relation in a wide channel of 0.984 m width under free-flow condition. Since the role of CFD is increasingly becoming prominent in present times, a numerical study using ANSYS-FLUENT was also carried out to ascertain its relevance in predicting flows around complex structures like PKW. Further, the tailgate was closed to render the PKW's outlet from partial to fully submerged conditions. The effect of these submerged outlets was studied for any changes in the discharging capacity of the PKW. The study shows RPKW to be more hydraulically efficient than TPKW9 for the model geometry. Further, the study finds that under partial to full submergence of PKW outlets, both PKW units' discharging capability remains unchanged.

Key words | discharge capacity, experimental study, numerical study, outlet submergence, piano key weir

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HIGHLIGHTS

- The present study focuses on the head-discharge relationship of RPKW and TPKW9 in a channel of 0.984 m width.
- The study shows rectangular PKW to be more hydraulically efficient than TPKW9 for the same upstream-downstream crest length.
- The numerical study using ANSYS-FLUENT supported the findings of experimental study.
- Partial to full submergence of PKW outlets has negligible effect on its discharging capacity.

NOTATION

PKW	piano key weir
RPKW	piano key weir with rectangular plan
TPKW9	piano key weir with trapezoidal plan and $\alpha = 9$ degrees
Relative ratio (r)	increased discharge ratio (Q_{PKW}/Q_W)
B_i/B_o	length of downstream/upstream cantilever overhang
B_b	base length
T_s	sidewall thickness

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g	acceleration of gravity (m^2/s)
H	water head at sufficient distance upstream of PKW (upstream flow depth measured relative to the weir crest) (m)
h	water head at middle of the lateral crest of PKW (m)
L	total length of the PKW's spillway front (developed crest length) (m)
P	vertical height of PKW (m)
Q	discharge (L/S)
C_d	coefficient of discharge under free flow condition
C_s	coefficient of discharge under submerged flow condition
Re	Reynolds number
V	velocity (m/s)
v	velocity component of velocity (V) along vertical direction (Y) (m/s)
W	total width of the weir/channel (m)
W_i/W_o	inlet/outlet key width ratio
X	coordinate along flow direction (m)
Y	coordinate in the direction of the vertical depth (m)
Z	coordinate along transverse direction (m)
α	angle between the lateral crest and the longitudinal direction in the direction of flow (degrees)
B	upstream-downstream lateral crest length of PKW

INTRODUCTION

Any transverse structures constructed in rivers or any flowing water body, such as dykes, bridges, weirs, and so on, tends to affect the natural flow (Yu *et al.* 2015) and hence create turbulence in the channel. The turbulence created in the open channel flow is also dependent on the shape of the channel; that is, rectangular, compound or trapezoidal and so on (Pandey *et al.* 2019a; Pu 2019; Pu *et al.* 2020) and plays a vital role in the sediment transport within the channel (Singh *et al.* 2020). The effect of sediment scouring around hydraulic structures like bridges, piers, and dykes has been studied by various researchers (Pandey *et al.* 2018, 2019b, 2020; Nhu *et al.* 2020; Tripathi & Pandey 2021). Weirs are also transverse hydraulic structures used extensively for water level moderation, channel stabilization, flow discharge measurement and control and environmental improvement. For achieving these goals, the weir must have high hydraulic functioning, structural feasibility and social sustainability. Since extensive studies of flow over weirs have established that a weir's discharge capability depends mostly on the crest length, efforts to achieve the same have been carried out by various researchers over time. Optimizing the shape to achieve a hydraulically efficient design with less cost has to be studied to arrive at a solution.

Moreover, augmenting the discharges of already constructed gates and spillways also has to be investigated to extend the life and reduce the risk factor of overtopping such hydraulic structures. A weir's self-cleaning ability is also an essential factor to be considered while evaluating its life. Studies to achieve all such favorable outcomes have been carried out in the past, leading to different weirs' evolution.

Experimental and numerical studies on labyrinth weirs continue to better understand the flow around these structures (Daneshfaraz *et al.* 2020; Ghaderi *et al.* 2020a). Labyrinth weirs were also studied for their different plan geometries (Ghaderi *et al.* 2020b) and their use as a side weir (Abbasi *et al.* 2021). The piano key weir (PKW) is considered to be a modified form of labyrinth weir. Electricité de France built the first PKW at the Goulours dam in France in 2006 (Laugier 2007). A review of the PKW has shown it to be quite efficient compared to its counterparts (Abhash & Pandey 2020). A PKW has a much larger discharge capacity than a linear weir (Tiwari & Sharma 2017). It has a higher discharge capacity as compared to the improved labyrinth weir (Anderson 2011; Blancher *et al.* 2011; Lempérière *et al.* 2011; Anderson & Tullis 2012), it is very economical (Ouamane 2011; Paxson *et al.* 2013) as well as having a much higher self-cleaning ability (Sharma & Tiwari 2013; Noseda *et al.* 2019). PKW has also been shown to allow for recovery of global storage volume and risk of non-opening of gates in spillway use (Lempérière & Ouamane 2003). The gated PKW's discharge coefficient has also been studied by Akbari *et al.* (2019).

More than 20 parameters influence the discharge capacity of PKW. Researchers have tried to bridge the gap in this area through various experimental and numerical studies. A basic unit of PKW was defined by Pralong et al. (2011), consisting of two half inlets and one outlet. The discharge coefficient of an RPKW and TPKW can be found from the standard weir equation:

$$Q = \frac{2}{3} Cd \sqrt{2g} L H^{1.5}$$

where $C_d = f\left(\frac{H}{P}, \frac{L}{W}, \frac{Wi}{Wo}, \frac{B}{P}, \frac{Bo}{B}, \frac{Bi}{B}\right)$

Researchers have tried to find and refine empirical equations that can be used to find the discharging capacity of PKW.

Crookston et al. (2018) examined two design approaches (a) empirical equations (simple and complicated) and (b) CFD studies used by researchers to estimate the discharge from PKW. They have further contributed to the already available empirical equations and co-related the CFD data using 40 simulations. 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 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. 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.

Submergence of a weir is defined when the tailwater exceeds a specific limit above the weir's crest to increase the upstream head for a given discharge. Submergence relationships have been studied by researchers(Villemonte 1947; Borghei et al. 2003). The labyrinth weir was also studied for submergence criteria (Falvey 2003; Tullis et al. 2007).

Khassaf & Al-Baghdadi (2018) experimentally studied the behavior of the piano key weir under submerged flow conditions. They concluded the discharge reduction factor (Cs) to be mainly influenced by the submergence factor ('S'). The discharge reduction factor (*Cs*) is influenced negligibly by the parameters L/W, Bi/B and P_d/P, where P_d is the dam height.

Kabiri-Samani & Javaheri (2012) also performed an experimental study on free and submerged flow in PKW conditions and gave analytical formulas. They conducted a submergence test on each weir configuration, and by sensitivity analysis, the relevant parameters for free (C_d) and submerged flow conditions (C_s) were analyzed.

Various researchers in this field have always pondered the advantages of numerical study. A numerical study has the advantage of lower cost and time savings incurred in evaluating each physical prototype. However, this does not necessarily obliviate the need for physical modeling. Physical modeling is required for the validation and verification of the results of CFD. Complex flow geometry of PKW, sediment transport capability, aeration requirements, site conditions, downstream energy dissipation and so on, presents limitations along with the scaled physical models used in labs. Hence, the growing need to combine the CFD and physical models has become necessary to combat the limitations and present a thorough understanding of factors involved in the study of flow around PKW. Various numerical studies to determine the effects of physical parameters on the discharge efficiency of PKW have been studied by researchers (Erpicum et al. 2012; Cicero et al. 2013; Abrari et al. 2015; Ghasemzadeh et al. 2015; Bremer & Oertel 2017; Eng & Lennart 2018; Hu et al. 2018; Amiya Abhash 2019; Chahartaghi et al. 2019).

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, and found that the geometrical adaptations decrease the efficiency of PKW for low heads ($H/P < 0.15$) compared to PKW without any adaptations.

Khassaf & Al-Baghdadi (2015) expressed the discharge capacity as a function of sidewall angle and sidewall inclination angle, which are α and β respectively for non-linear PKW.

The side weir flow characteristics of PKW, labyrinth and linear weirs have been compared and presented by Karimi et al. (2018). The self-cleaning process for labyrinth weirs under four sediment types have been studied by Gebhardt et al. (2019). Upstream of PKW has been studied for vertical velocity components for their role in sediment passage downstream (Tiwari & Sharma 2016; Noseda et al. 2019; Amiya Abhash 2021). Similarly, PKW have been studied for scour formation downstream (Jüstrich et al. 2016; Pfister et al. 2017; Yazdi et al. 2021). Trapezoidal geometry of PKW in a curved channel has been studied by Saghari et al. (2019) for their discharge capacity.

Research objectives

The rectangular plan geometry of PKW has been studied most by researchers. Other plan forms like trapezoidal or arched still need further experimental research to understand their flow hydraulics. The present study focuses on the two different plan forms of PKW; that is, RPKW and TPKW9, for their head-discharge relation in a wide channel of 0.984 m width in free-flow condition. The study was conducted to find the hydraulically efficient plan form among the two. A numerical study was also conducted to ascertain if it can correctly predict the flow around PKWs. Further, the tailgate was closed to render the outlets of PKWs partially to fully submerged and see its effect on discharging capacity and changes in the upstream head.

METHODS

Experimental setup

The PK weir testing was conducted in a laboratory flume measuring a magnitude of 0.984 m wide, at 0.5 m deep and 24 m long. The flume bed and sides were made of bricks plastered with fine sand and punning. After being collected in a tank, water entered the flume separated by a vertical baffle wall to create a relatively uniform approach flow condition. The PKW was installed at a distance of 7 m from the tank with a baffle wall. The tailgate was positioned 8 meters beyond that. Finally, the water was made to fall into another stilling well before reaching the linear weir for the discharge measurement. The linear weir was also positioned at a distance of 8 meters from the stilling well. After flowing over the linear weir, the water collected into the underground sump, from which it was pumped back into the flume. The models used in the experimental study are presented in Figure 1(a) and 1(b). The experimental setup is as shown in Figure 1(c).

Table 1 summarizes the different models and their dimensions used for the study. Four cycles of PKW were used for all the models in the study. A total of ten discharge measurements were made for each PKW model. The water head was measured with the help of a point gauge with ±0.1 mm reading accuracy. The flow depth was measured along eight individual inlet and outlet points on PKWs, and their average was taken as the crest head for further analysis and study purposes.

The entire setup rested upon an underground sump from where water was circulated in the channel. The experiment was run for free overflow and partial closure of gates to produce partial to complete submergence of outlets of PKW. The head was measured from the well installed near the linear weir, and the discharge was then read from the graph available in the Hydraulics lab of IIT (BHU), Varanasi. The discharge was varied from as low as 3 L/s to 40 L/s.

Numerical setup

Numerical simulations were performed on the ANSYS-Fluent platform, and the results were compared to the experimental results. Reynolds-Averaged Navier Stokes Equation using the Finite Volume Method was used to solve the problem numerically.

The simulations were performed on a 20 core CPU using a parallel solver option and double precision. Flows over PKW and TPKW9 were modeled on half PKW with a channel height of 0.5 m. A total length of 3.0 m was created for the numerical simulations with an upstream length of 2.5 m. Mesh near PKW was refined further so that discretization error could be reduced. A total of 1.35 million mesh cells were introduced in the channel for our study. The same meshing technique was adopted for the two geometries to ensure a standard reference. The top and outlet were specified as 'pressure outlets,' while the inlet was specified as 'velocity inlet.' Both sides of the channel were taken as 'symmetry,' while the bottom and PKW were treated as 'walls.' The numerical study was carried out for four discharges (6.67, 12, 20 and 29 L/s) in free-flow conditions. Each of these discharges was selected as they mark a change in the nappe flow over the PKW.

The flow over PKW has been categorized as a transition from a clinging nappe to leaping and then to a springing nappe flow for different values of H/P ratio. Machiels et al. (2011) had established that for H/P between 0.09 and 0.1, the nappe on the lateral crest is free, while for $0.16 \leq H/P \leq 0.17$ on the downstream crest of the inlet, the nappe is wholly aerated. Changes in nappe of flow have been observed in our experimental and numerical study.

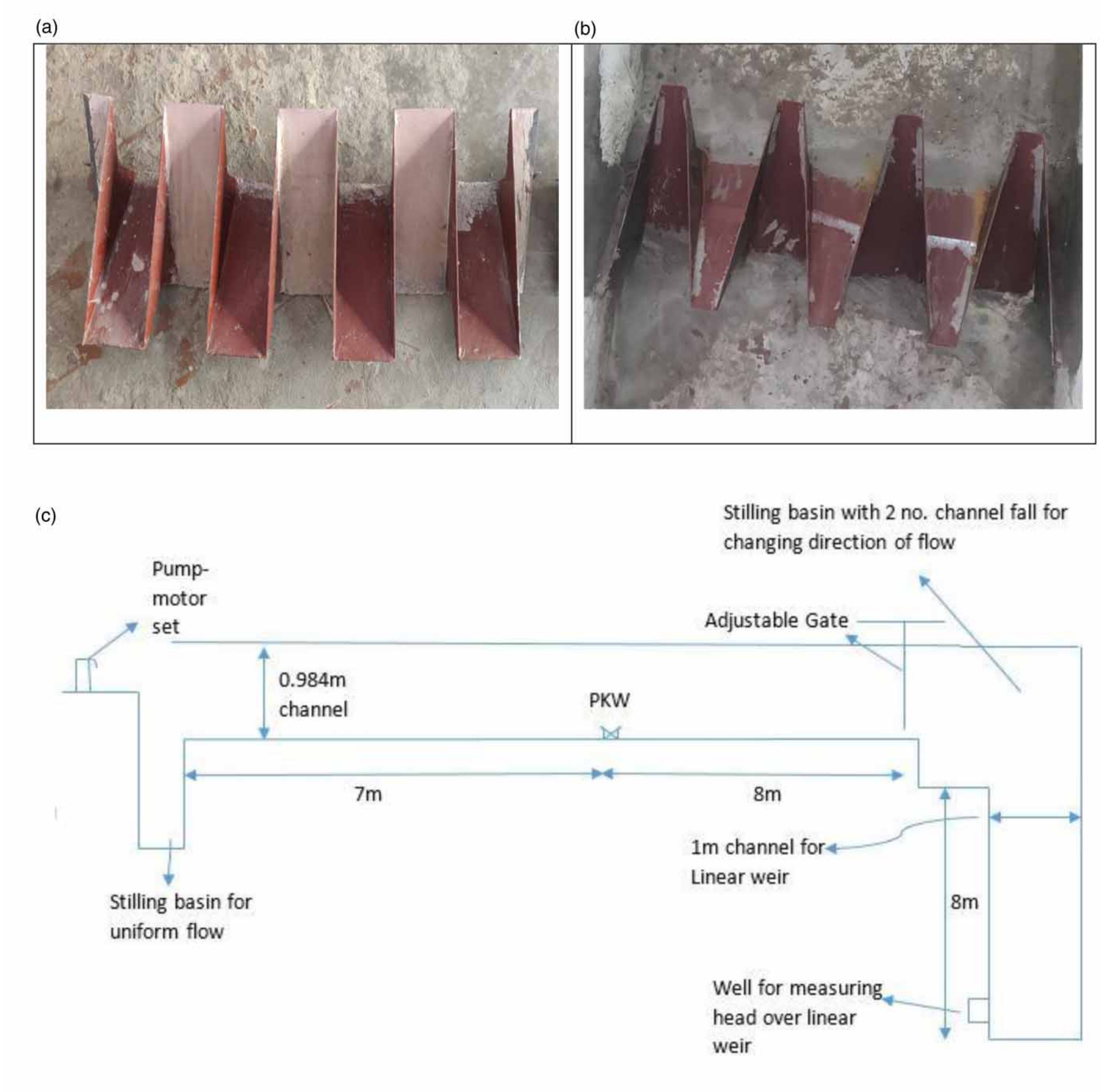

Figure 1 | Models used in the experimental study (a) RPKW, (b) TPKW9 and (c) experimental setup.

Table 1 | Geometric parameters of PKWs

PKW	P(mm)	B(mm)	Bi(mm)	Bo(mm)	Bb(mm)	Wi(mm)	Wo(mm)	α (degrees)	No. of cycles
RPKW	150	400	100	100	200	122	122	0	4
TPKW 9	150	400	100	100	200	24	78	9	4

The PISO k-Ɛ model was selected for the study as per the references available. The time step was kept small at 0.0005 and was varied to 0.005 seconds with 20 no of iterations to reduce the linearization error. The equations were solved numerically, making use of conservation of mass and momentum for all flows.

RESULTS AND CONCLUSIONS

Discharge-head relationship of PKW models

Discharge (Q) vs. head at the crest (h) for RPKW has been plotted in Figure 2(a). The numerical results of the four discharges have also been plotted to compare the experimental and numerical results. Similarly, Figure 2(b) illustrates the discharge-head relationship of TPKW9 and compares the numerical results with the experimental study. Both the result shows the numerical study to be in close proximity with the experimental results. The errors are well within the permissible limits.

A comparison of the RPKW and TPKW9 discharge-head relationship has been plotted in Figure 2(c). The results show RPKW to be more hydraulically efficient than TPKW9 for the same number of cycles and upstream-downstream distance (B) and the same channel width.

The efficiency of an RPKW and TPKW9 has also been compared with a linear weir. The comparison has been shown in Figure 3(a) and 3(b), for RPKW and TPKW9 respectively. PKWs, at higher heads, tend to behave like a linear weir. Hence, the increased discharge 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), further illustrates the superiority of PKWs (Ribeiro *et al.* 2007).

$$r = Q_{PKW}/Q_W \quad (1)$$

Since our experimental model, the H/P ratio is much smaller; we can see the high hydraulic advantage of PKWs compared to the linear weir.

Observations under partial to full submergence of the outlet of PKW

RPKW and TPKW were both observed for partial and complete submergence of outlet portions of PKWs. The gate was partially closed to create partial submergence in the outlets of PKWs. The outlet was fully submerged in three stages to observe any changes in the head over the crest of PKWs or the upstream head. The water upon the raised downstream first begins to rise in the outlet slope. The rapid water falling from the outlet meets the still water downstream, and dissipation of energy takes place at the downstream outlet of PKWs (Figure 4(a) and 4(b)). The water falling from the inlet forms a beautiful water film all along the crest length of PKW. This water film's shape is governed by the plan form of PKW, as shown in Figure 5(a) and 5(b), respectively, for RPKW and TPKW9. The water level downstream rises but without affecting the head on the crest of PKW. The head over the crest was measured at all these stages to detect any changes. On further increasing the downstream water level by closing the gate further, the triangular wedge as seen in both RPKW and TPKW9 changes into a rectangle with a curvy boundary as shown in Figure 4(b) and 4(c).

We can see in Figure 4(c) that about 80% of the PKW outlet is submerged. The curvy rectangular boundary has a distinguish ring formation connecting one outlet of PKW to another. The rings become further distinguished, as shown in Figure 4(d), when almost 95% of the outlet is submerged. The head over the crest, though, remains the same for both PKW and TPKW9 cases. Upon further closing the gates, we can see these rings die down. Small ripples of waves are visible, like in Figure 4(d), which ultimately get drowned as the downstream water level fully submerges the outlets of PKW.

CONCLUSIONS

PKWs are considered more hydraulically efficient than their counterparts both in new construction and in dam rehabilitation. They are structurally efficient, economical and present higher self-cleaning abilities. An experimental study was carried out on two different plan forms of PKW; that is, RPKW and TPKW9, to determine their hydraulic efficiency. The graph of discharge versus head was plotted for each weir geometry. Also, the head was compared with a linear weir since, at higher heads, PKW tends to behave like a linear weir. A numerical study was also done on four of these experimental discharges using ANSYS-FLUENT to study its relevance in predicting flow around complex structures like PKW. The experimental values and numerical values were compared for errors. The experimental study showed RPKW to be more hydraulically efficient than TPKW for the same number of cycles in a fixed channel width. The interference wedge was more prominent in the TPKW plan. The nappe was clinging in nature

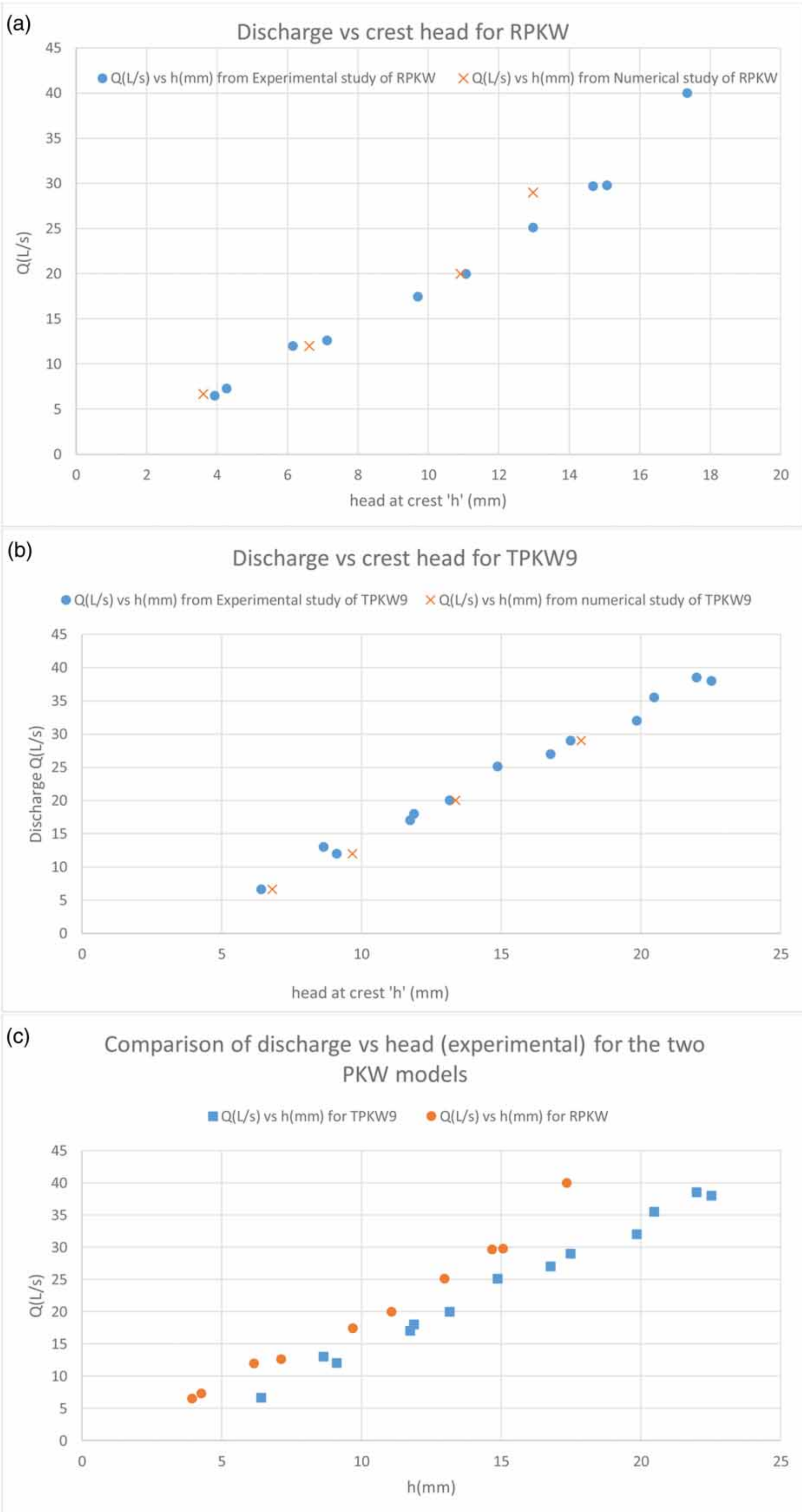

Figure 2 | (a) Comparison of an experimental and numerical study of discharge vs. head at the crest for RPKW. (b) Comparison of an experimental and numerical study of discharge vs. head at the crest for TPKW9. (c) Comparison of experimental discharge vs. head at the crest for RPKW and TPKW9.

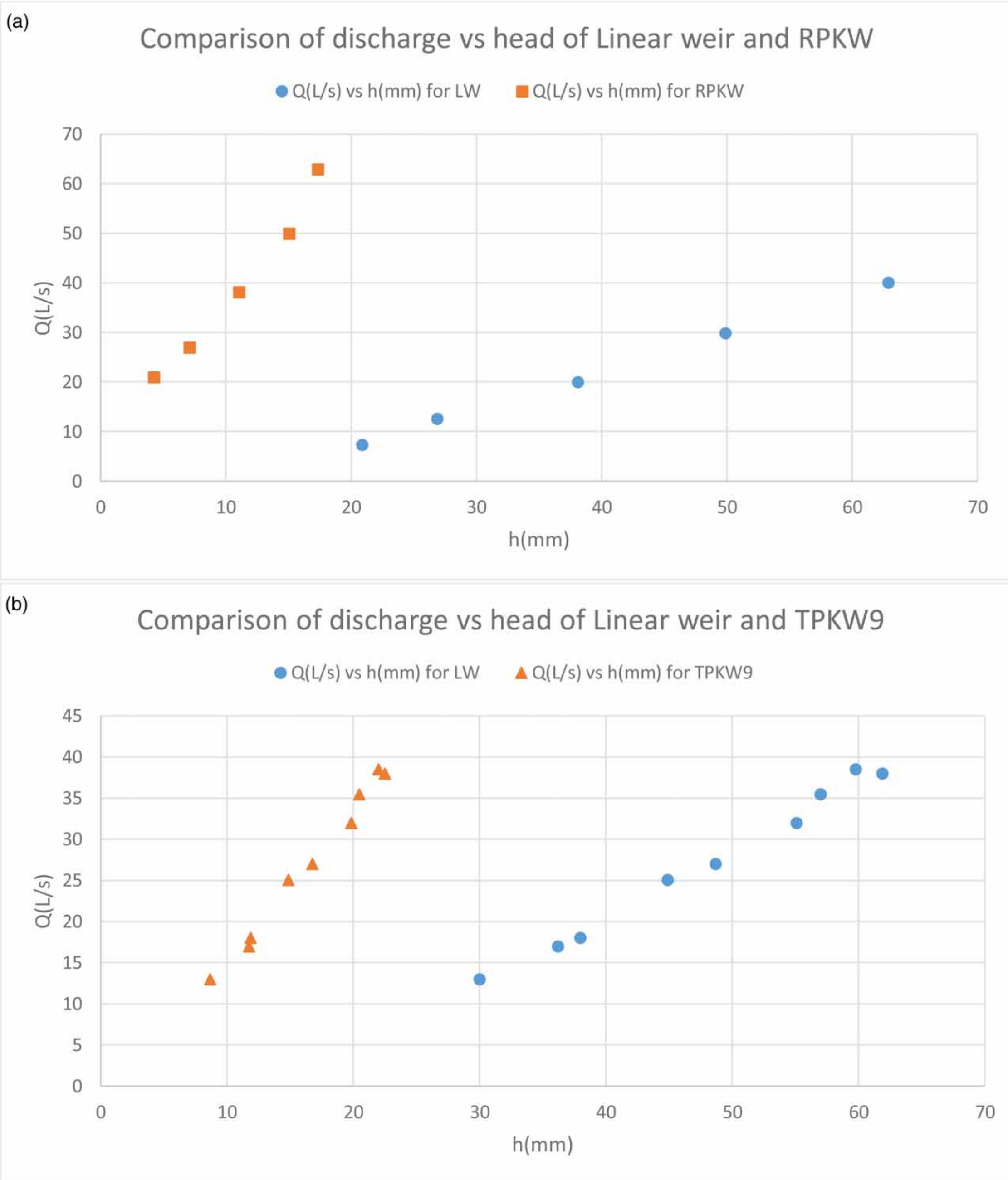

Figure 3 | (a) Comparison of experimental discharge vs. head at the crest for RPKW with that of a linear weir. (b) Comparison of experimental discharge vs. head at the crest for TPKW9 with that of a linear weir.

for most of the discharges for both the plan geometries. The discharging capacity of both the plan forms of PKW was much higher than that of weirs. The study using ANSYS suggested that numerical simulations can predict the flow around PKWs accurately and within permissible error limits, thereby saving cost, time and economy.

The outlets of PKW were partially to fully submerged by closing the tailgates, and patterns emerging from this closure were studied. The study showed that partial to full outlet submergence had a negligible effect on the head measured at the crest of PKW within the experimental limits of the h/P ratio. Head over the crest of PKW increased only after full

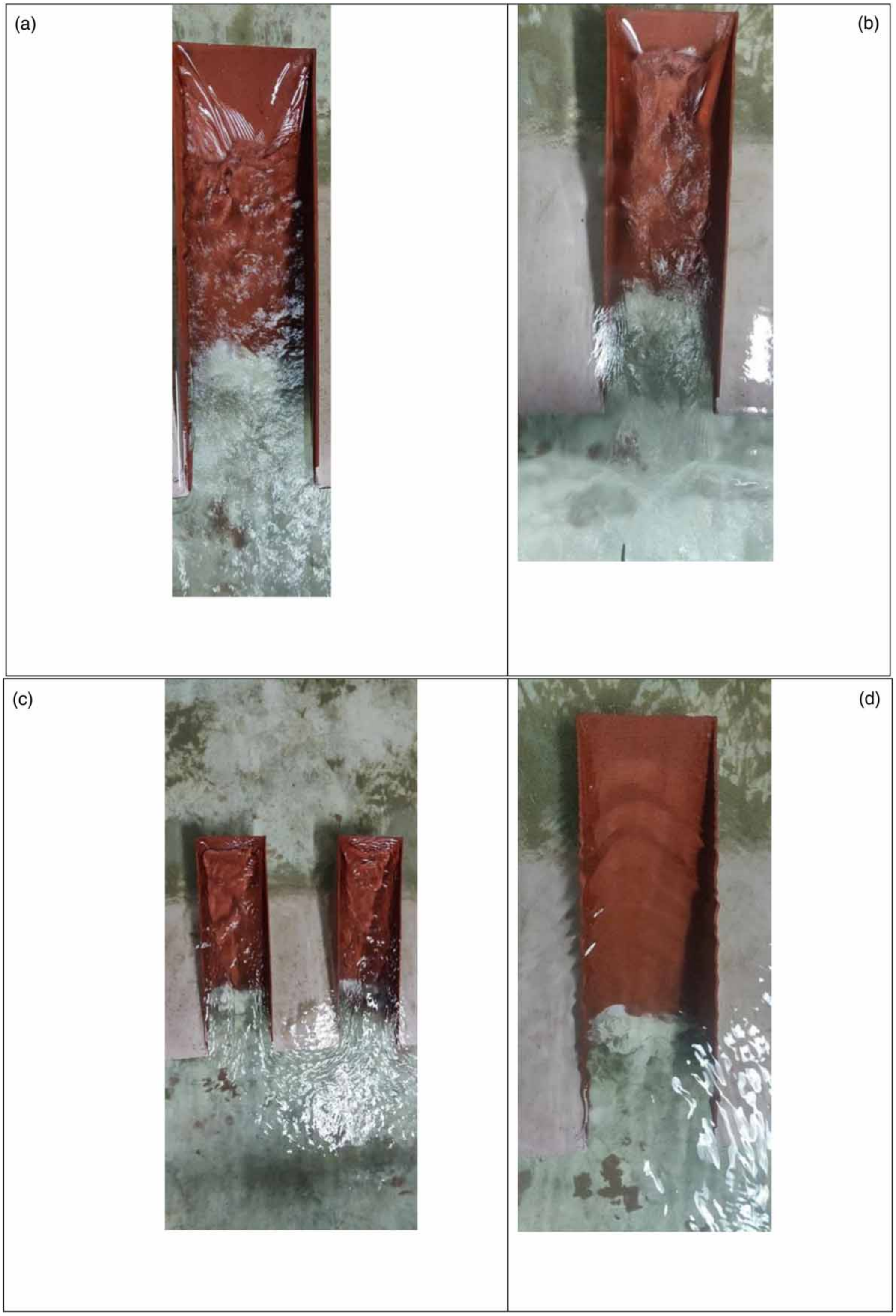

Figure 4 | Different stages in submergence of the outlet of RPKW.

Figure 5 | Continuous water film in PKWs under partial submergence. (a) Continuous water film running around inlet-outlet of RPKW. (b) Continuous water film running around inlet-outlet of TPKW9.

submergence of outlets of PKW and downstream water level being higher than the height of PKW (P). The present study hopes to contribute to the literature on developing and refining discharge-head empirical equations for RPKW & TPKW. Sediment passage in the upstream and scour formation in the downstream need to be studied for different plan geometries of PKW. Energy dissipation is another area that demands attention for these PKW geometries. A combination of experimental and numerical studies will lead to a better understanding of these grey areas in the future.

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CONFLICT OF INTEREST

None.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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