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Introduction and investigation of a large-scale piano key weir fabricated via rapid prototyping

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Abstract: *Piano key weirs (PKW) are novel hydraulic structures, characterized by an increased discharge capacity, compared to regular weirs. Through the last decades, experimental studies have mainly focused on efficiency aspects and design regulations. Therefore, often small scaled experiments were conducted in hydraulics laboratories in which model geometries were produced with materials like acrylic glass. But also in recent practices, 3D printing techniques are being used to plot small-scaled piano key weir configurations up to 30 or 40 cm width. The present investigation focuses on a large-scale 3D printed PKW with a total width of 1 m featuring quarter round crest shape in upstream direction. The weight of the printed structure is approximately 30 kg and 8 days continuous plotting process were necessary to produce the weir – consequently, it is the largest 3D printed PKW up-to-date. The plotted PKW was installed at Helmut-Schmidt-University's new hydraulics laboratory within a 20 m long and 1 m wide flume. Discharges ranging from 20 to 330 L/s were used to investigate the hydraulic performance of this printed PKW with a height of 40 cm. Results depict that the scale difference between models of 30 cm and 40 cm in height is not significant if the objective is to study discharge coefficients. 30 cm models can reproduce similar flow properties at a relatively smaller cost and less preparation time. Moreover, patterns of nape detachment were observed at the downstream crest lip, indicating the influence of the printing layer height in inducing undesired flow separation for relative upstream heads above 0.33 that could likely affect the nape trajectory.*

Keywords: *Discharge coefficients, Large-scaled model, Piano key weir, 3D printing*

1. Introduction

For their advantages in terms of achieving better hydraulic performance, piano key weir (PKW) research became a topic of interest in contemporary studies of hydraulic structures. These hydraulic structures allow highly effective passing of a range of discharges with smaller upstream heads compared with regular weirs (Eslinger and Crookston 2020). Recent laboratory scale studies are carried out to assess hydraulic performance and scale effects among piano key weirs of different sizes ranging from 1:7 to 1:25 relative to a prototype (Erpicum et al. 2016). Several investigations were carried out in the past with the aim to optimize the geometry of PKW while maintaining favorable hydraulic performance (Shen and Oertel 2021; Cicero and Delisle 2014; Machiels et al. 2014; Ouamane and Lempérière 2006), mainly discharge coefficients and energy dissipation processes. The implementation of PKW in flood release structures at dams or in-channel applications has been encouraged through intensive experimental and numerical studies, while some research (Ribeiro et al. 2012) even proposed a preliminary design guideline for practical applications. The use of large-scale laboratory models is ideally preferred so that adverse scale effects can be minimized, and different flow fields or geometric variables can be thoroughly investigated. However, this is often limited by available flume sizes and especially discharge capacities of a particular hydraulics laboratory. Some flow field properties, such as air entrainment, are better understood in laboratories when large-scale models are used. In that case, the effect of surface tension force near the free surface gets less significant compared with the inertial force and turbulence stress, especially in prototypes (Oertel 2019; Erpicum et al. 2016; Heller 2011; Chanson 2009). Hence, while maintaining the minimum criteria, for instance $H_T \geq 0.03$ m (total head above the weir) or Weber number ≥ 54 (Erpicum et al. 2016), such large-scale models are more convenient to visualize and study air entrainment as well as nape trajectory. In the absence of large-scale modeling capabilities, to investigate discharge coefficients and nape behavior at low heads for small scaled PKW models, Oertel (2019) has also proposed a surface tension correction solution so that underestimation of discharge coefficients for small heads can be minimized for such experimental campaigns.

The current study aims on introducing a large 3D printed PKW model that has been developed at Helmut-Schmidt University's (HSU) hydraulics laboratory (Figure 1). The 900 m^2 laboratory is currently under construction with a final discharge capacity of up to 1500 L/s. A first horizontal flume was installed with a length of L_f = 20 m, a width of W_f = 1.0 m, and a height of H_f = 1.0 m. A 500 mm pipe system and two 175 kW pumps connected to a 300 m^3

storage basin provide the discharge. Moreover, this investigation was motivated by the advantages of time- and cost-effective rapid prototyping practices in hydraulics laboratories. The practice of large-scale model preparation of complex geometries has been currently standardized in the newly established HSU's hydraulics laboratory.

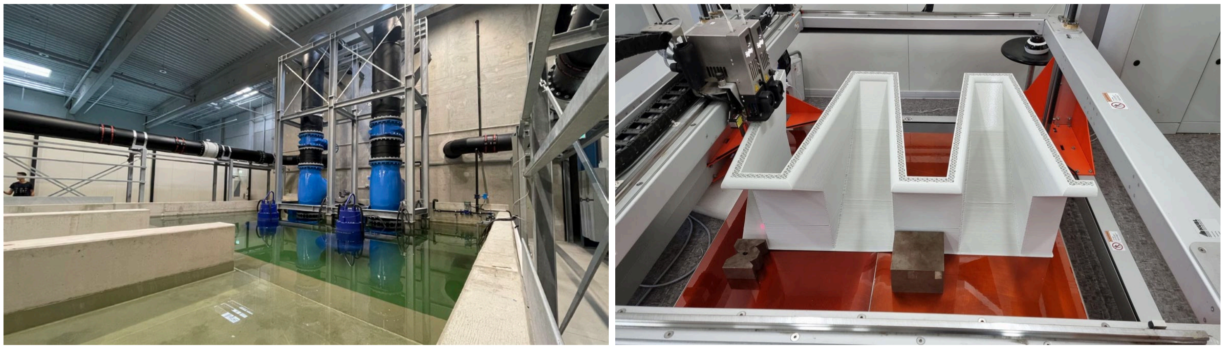

Figure 1. HSU's new hydraulics laboratory, left: two 175 kW pumps and DN500 pipe system, right: BigRep One 3D printer with 1 m^3 plot volume (1×1×1 m) and partially finished 40 cm high and 100 cm wide PKW model in printing process.

2. Model preparation

The current experimental measurement campaign was commenced by 3D printing a trapezoidal PKW to fabricate the desired experimental model (Figure 1, right). A BigRep One 3D printer was used to plot the large-scaled PKW with a width of 1000 mm and a height of 400 mm (8 days 24/7 printing time, ~30 kg filament weight), representing the largest 3D printed PKW model up-to-date (see Figures 1 and 2). Polylactic acid (PLA) was used with a layer height of 0.6 mm in horizontal orientation with an installed nozzle diameter of 1 mm. The model was designed to have a quarter round upstream crest lip shape with a radius of 20 mm. A developed innovative system was used to fix the model within the flume without any flow disturbing influences. Table 1 shows all model dimensions for the new plotted PKW model and for all compared previous models. The notation P_{40} is used to indicate the weir height (40 cm), likewise for the other three models.

The current PKW model was plotted as an extension of previous models in which all the geometries and test discharges were scaled and parametrized through Froude similarity relative to the other models' main parameters, presented in Table 1. It is imperative to mention that the printing layer heights are independent of the scaling process.

Table 1. Geometric features of studied and compared PKW models

Geometric parameter	Unit	Model dimension			
		P_{40}	P_{30*}	P_{20*}	P_{10*}
P (weir height)	[mm]	400	300	200	100
B (weir length)	[mm]	640	480	320	160
L (total crest length)	[mm]	3677	1103	1103	1103
W (weir width)	[mm]	1000	300	300	300
W_i/W_o	[-]	1	1	1	1
T (wall thickness)	[mm]	40	30	20	10
R (crest radius)	[mm]	20	15	10	5
printing layer height	[mm]	0.6	0.4	0.4	0.2

* *Previous models, printed on a Creality CR-10 max.*

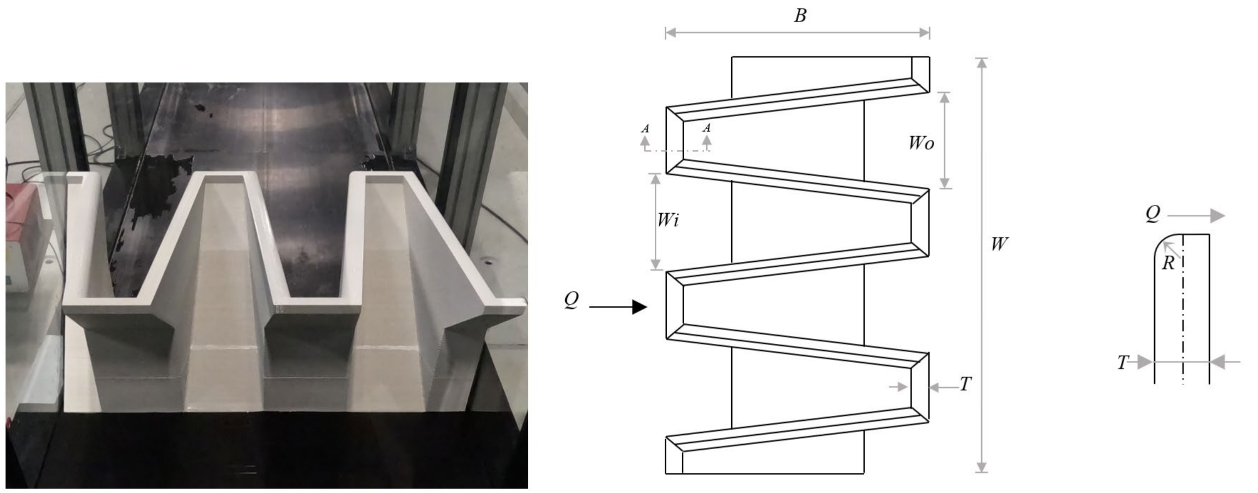

Figure 2. Investigated PKW model, left: flume installation (looking in upstream direction), right: geometric features

3. Experimental setup

Model runs were conducted in the previously mentioned rectangular flume ($L_f = 20$ m, $W_f = 1.0$ m, $H_f = 1.0$ m) at the hydraulics laboratory of Helmut-Schmidt-University, Hamburg, Germany. The maximum discharge capacity for the current experimental setup was approximately 350 L/s. Flow depth measurements were performed using an ultrasonic sensor (Microsonic; mic+130/IU/TC, signal range: 200 to 1300 mm, accuracy: ± 1%) installed 2 m (5*P*, where *P* is the weir height) upstream of the PKW. Discharges were measured using a magnetic inductive flow meter (MID, Krohne Optiflux, accuracy ± 0.3%). The flume entrance included perforated vertical steel plates within the inlet box as flow straighteners to guarantee a smooth approaching flow. No control gates were used at the downstream end of the flume and a free outflow was achieved. Measurements were conducted for discharges from $Q = 20$ to 330 L/s. Each flow depth for varying discharges was measured for a duration of 30 seconds with a sampling frequency of 75 Hz. Appropriate data filtering (removing outliers by standard deviation criteria) was undertaken to obtain an average flow depth value from recorded time series. Additionally, image acquisition was carried out using a GoPro Hero 10 camera and pictures are then used for qualitative assessment of flow behavior at the PKW crest under the proposed test discharges.

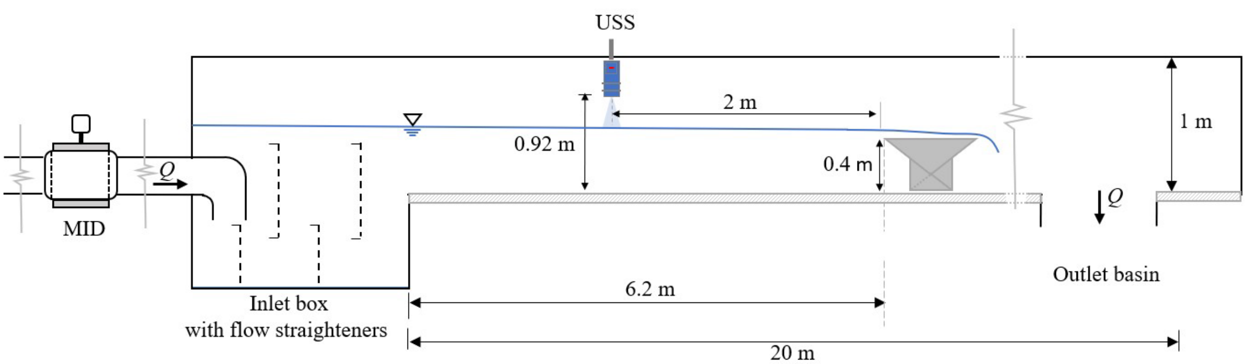

Figure 3. Experimental model setup sketch, including PKW and USS positions (non-scaled drawing)

4. Results and discussion

4.1. Scale effects

A comparison of discharge coefficients between the current 40 cm model and previous experiments (for 10, 20, and 30 cm models) was carried out based on H_tP^{-1} values ranging from 0.054 to 0.5. Resulting discharge coefficients indicated the expected phenomenon at low heads in which the current large-scaled 40 cm model prevails with a relatively higher C_{dL} value, while no significant differences were observed for $0.15 < H_tP^{-1} < 0.35$, as presented in Figure 4. In some areas for $H_tP^{-1} > 0.35$, small deviations can be found that may be caused by small nape detachments (flow separation) at the tip of the outlet keys which will be discussed within Chapter 4.2. Discharge coefficients were calculated using the Du Buat equation:

$$C_{dL} = \frac{3Q}{2L\sqrt{2g}H_t^{1.5}} \tag{1}$$

Where: C_{dL} = discharge coefficient (related to total crest length), Q = discharge, L = total crest length, g = acceleration due to gravity, H_t = total upstream energy head = $v^2(2g)^{-1} + h_t$, v = depth-averaged upstream velocity, h_t = overfall height.

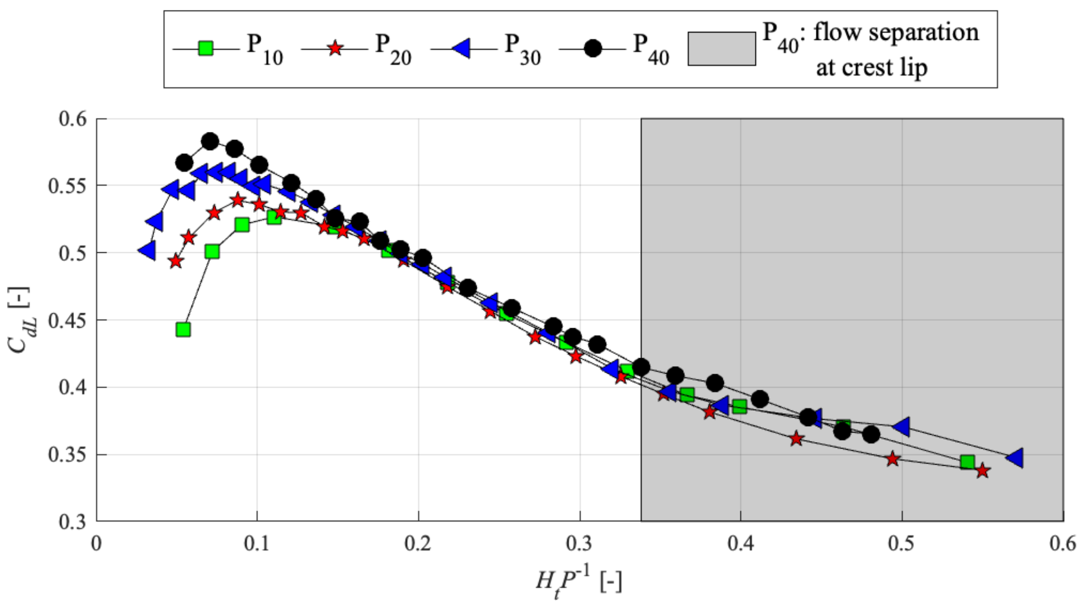

Figure 4. Discharge coefficients of investigated PKW models

Often, large scale modeling in hydraulic laboratories is taken as a better option but comes with financial and technical challenges. Ideally, near prototype physical models in hydraulic laboratories reproduce the flow parameters efficiently as the scale effect appears negligible compared with smaller ones. However, limitations still exist on the aspects of preparation cost and time when it comes to the largest possible model size that can be fabricated. In case of PKWs as investigated in the current study, unlike the 10 cm and 20 cm models, the results illustrate that an increment in model scale or size from 30 cm to 40 cm did not depict adverse deviations in terms of discharge coefficients at low heads when compared at same discharges and H_tP^{-1}. This indicates the use of a 30 cm high PKW for laboratory scales could be taken as sufficient size to study discharge coefficients instead of 40 cm models, which saves preparation cost and time. However, because this investigation didn't include measurements of other complex parameters such as air-water flows downstream, a remark could not be put whether these 30 cm and 40 cm high PKW models reproduce relatively similar results (like discharge coefficients).

Furthermore, the influence of surface tension at low heads was evident (supporting previous studies) while comparing the two scale extremes of this study: 10 cm model vs. current 40 cm model (Figure 5). In this case, a one-to-one comparison shows a slight departure of C_{dL} values (beyond a 5% error bound) against the Froude similarity at low heads ($0.054 < H_tP^{-1} < 0.07$) as the model size gets smaller relative to the current P_{40} model (Figure 5).

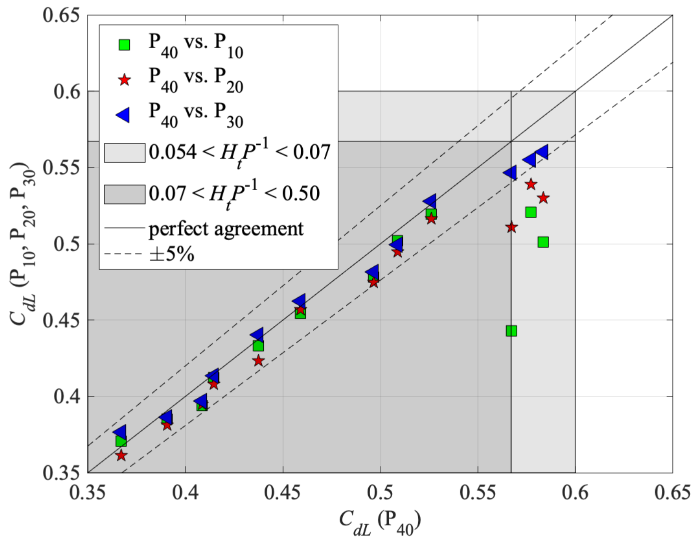

Figure 5. Relative comparison of discharge coefficients indicating scale effects (at relatively similar values of H_tP^{-1})

Apparent differences in nape trajectories were also noticed while comparing the flow behavior of the 20 cm with the current 40 cm model (see Figure 6), depicting the adversity of scale effects prevailing at small PKW models. This effect was reflected by the outcome of corresponding discharge coefficients at low heads ($0.054 < H_tP^{-1} < 0.07$) for these two models as shown in Figure 5.

Figure 6. Scale effects and its influence on nape trajectory for comparable discharges ($H_tP^{-1} = 0.05$), left: P_{20} model, right: P_{40} model

4.2. Effect of printing layer height on flow separation

Under the current setup, as discharges increased above 220 L/s ($H_tP^{-1} \geq 0.338$ m), significantly identifiable flow separation was observed at the tip of the crest (Figure 7). With close qualitative examination, the printing layer height (0.6 mm) of the 40 cm PKW depicted a direct influence on the nape trajectory at the upstream side of the crest lip. This behavior indicated the presence of undesired flow fields at higher discharges and the effect tends to slightly elevate the nape trajectory with unevenly distributed cavities in the spanwise direction over the weir crest (Figure 7).

For 3D printed models it must be noted that these represent a time- and cost-effective fabrication process for hydraulic laboratories. But the optimum printing layer height should be carefully chosen so that the crest lip roughness influence is maintained as minimum as possible. The printing layer height was seen to only affect the nape at the crest lip of the outlet keys where the flow accelerates compared to the side crest and the inlet keys. This result probes a hint for future model preparation methods using 3D printers that, it is essential to avoid or minimize forced roughness that could arise from the choice of printing layer heights so that undesired interferences on the nape behavior could be reduced. The observed flow separation beyond the specified discharge did not induce a major change in resulting discharge coefficients (see Figure 4), however this should be taken into account when investigating the nape trajectory. Smaller printing layer heights or surface finish mechanisms might reduce layer influences. Nonetheless, it could be expected that such flow separation might also occur on side walls if the upstream head further increases. This could lead to a slightly rise of the nape, reducing the discharge coefficient compared with model runs without flow separation.

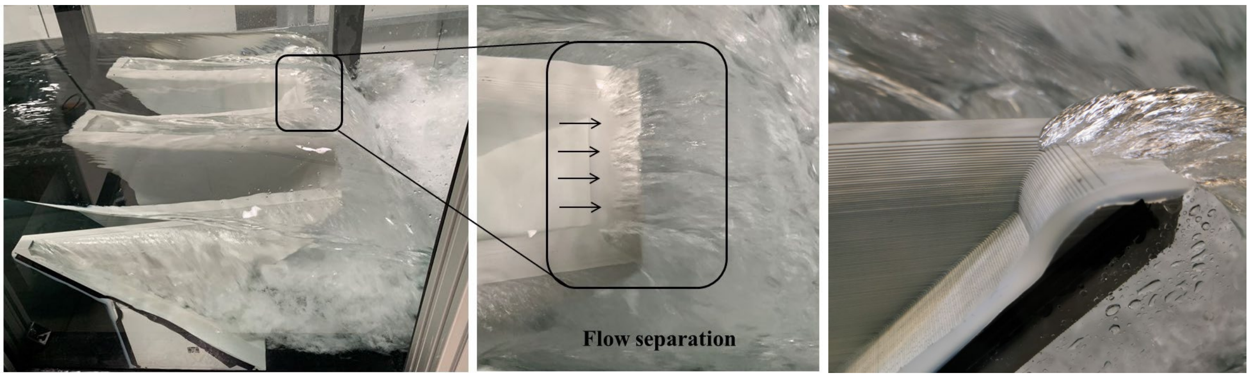

Figure 7. Observed flow separation at the upstream side of the crest lip (P_{40} model), left: overview, middle: top view detail, right: side view detail

5. Conclusions

With the aim of evaluating the advantages from developing and implementing experimentations using large scale models in hydraulic laboratories, this study undertook an assessment of a 40 cm high piano key weir model prepared via 3D printing. The test discharges covered a range in which the hydraulic performance can be clearly compared with other smaller models of 30 cm, 20 cm, 10 cm height. The following remarks are learnt from this experimental study of 3D printed PKWs:

- To investigate common hydraulic performance parameters of PKWs (in this case, discharge coefficients and rating curves), 30 cm high PKW models can be considered adequate to provide comparable results as the 40 cm models with minimum scale effects between them. Hence, 30 cm high PKW models can simply be used to study discharge coefficients while maintaining minimum cost and preparation time. Although this can be seen as an advantage, the size adequacy of these models (30 cm or 40 cm high PKW) may not be taken strictly sufficient to study every hydraulic parameter (such as air entrainment) because such complex flow filed properties are not covered in the current investigation. Hence, further studies are also encouraged to fill this gap in which optimum model sizes can be specified for air entrainment studies at minimum preparation cost and time of a physical model via 3D printing.
- The adverse deviations of discharge coefficient values for the same H_tP^{-1} among 40 cm and 10 cm models were evident at low heads, indicating the effect of surface tension will be important for small model scales. Considering the 40 cm PKW is a large-scale model, the comparison enhanced visualization of such scale effects.
- Furthermore, printing layer height (0.6 mm) of the 40 cm weir was observed to intervene with the flow pattern right at the upstream side of the crest lip at the outlet keys for larger discharges ($Q > 220$ L/s, $H_tP^{-1} > 0.338$). Although, this did not significantly alter the trend of the discharge coefficient for high heads, the behavior gives an indication that the nape trajectory could be directly affected depending on 3D plot parameters. It should be avoided by using relatively smaller layer heights or by an implementation of a smooth surface finish during model preparation. Hence, for model heights above 30 cm, the use of printing layers height less than 0.6 mm can be considered as a reasonable measure to minimize the presence of undesired flow pattern at the crest lip.

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