The Piano Key Weirs: 15 years of Research & Development – Prospect

M. HoTa Khanh (VNCOLD) - Vietnam
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1. GENERAL – A BRIEF HISTORIC
General characteristics of the PKWs: A variation of traditional labyrinth weirs with rectangular planform and overhangs in streamwise direction to reduce the footprint.

The first studies and tests have been promoted and coordinated by Hydrocoop in 5 laboratories (France, Algeria, China, India and Vietnam) from 1998 to 2005.

The main goal of these first studies and tests was to facilitate preliminary design with the:
- Characterization of the main parameters of different PKWs.
- Elaboration of some «standard models», taking into account structural and economic considerations to facilitate cost estimation and comparison with other alternatives.

The (symmetric) standard model type A with \( n=5 \).
- Determination of the rating curves \( (q_s \text{ vs. } H_u) \) for several “standard models”

* \( q_s \text{ in this presentation is } q_sW \text{ and not } q_sL \)

For the “standard model type A” of Hydrocoop, the rating curves are quasi linear with \( q_s = 4.3\sqrt{P_m H_u} \).

These curves allow to get directly the 3 main following outcomes which are paramount in the choice between a PKW and an ogee weir.

✓ **The increase of the specific discharge** \( \Delta q_s \) for a given nappe depth \( H_u \).

✓ **The reduction of the nappe depth** \( \Delta H_u \) for a given specific discharge \( q_s \).

✓ **The ratio** \( r = \frac{q_{PKW}}{q_{Creager}} \) for a given nappe depth \( H_u \).
- Some different types of PKW proposed by Hydrocoop.

These varied PKW shapes (others can be imagined) allow finding the best fitted type depending on the different constraints of the project.

These constrains are linked to:
- hydraulic optimization,
- structural and construction constraints,
- operation requirements,
- economic consideration.

For example, for a long barrage founded on alluviums, a study shows that the type D or E (without overhangs) can be preferred to the type A for construction and economic reasons.
- The design and construction of several PKWs by EDF, after the first successful example of the Goulours dam in 2006, was the origin and the beginning of numerous tests concerning the PKWs by EDF-LNHE (France), HECE-ULg (Belgium) and LCH-EPFL (Switzerland).

- From 2004 to 2006 different PKWs for new dams have been studied in the Vietnamese hydraulic laboratories with the rapid construction of several of them.

- There are now several PKWs under design and construction worldwide.
2. THE PHYSICAL MODELS
2.1 Main issues and results for the PKW rating curves

2.1.1 Main issues

Due to the great number of geometrical parameters for the PKWs (about 30 parameters but 20 are generally sufficient):

- Need to apply a naming convention to facilitate the comparisons.

- Very numerous tests are required to find the relation between all these parameters, their variations and the resulting rating curves.

- Difficulty for the optimization of the design (in particular with the structural constraints), but also a great advantage with the flexibility of the design permitted by the large set of parameters.
2.1.2 Main results concerning the PKW rating curves

Many past and present tests are devoted to provide the rating curves of different types and sizes of PKW, their sensitivity with the extensive variations of the parameters and the conditions of approach.

The main following results are obtained:
- The principal parameters are: \( L, W, H_u/P \) and, in some cases, the ratio \( W_r/W_o \) and \( T_s \).
- As an additional spillway, a PKW is generally interesting, from an economic point of view, if \( H_u/P < 1 \).
- For a submerged flow, the decrease of \( q_{sub} \) is significant only if \( H_d/H_u > 0.6 \). Introduction of the notions of “efficiency” and “sensitivity”.
2.2 Examples of R&D with physical models

2.2.1. Mathematical forms for the “discharge coefficient” (or the ratio \( r = \frac{q_{PKW}}{q_{Creager}} \)) by different analytical approaches

- The research of a “discharge coefficient” \( C_w \) or the ratio \( r \) for the PKW.

  Example of a form giving \( X (r = e^X - 1) \) vs. \( H \) and the main characteristics of the PKW

\[
0.26 \left( \frac{P}{a} \right)^{1.4} \left( \frac{H}{P} \right)^{0.15} + 1.0056 \left( \frac{L}{W} \right)^{0.15} \left( \frac{P}{a} \right)^{0.15} \left( \frac{H}{P} \right)^{0.7} + 0.067 \left( \frac{L}{W} \right)^{0.3} \left( \frac{P}{a} \right)^{2} \left( \frac{a}{b} \right)^{0.25} \left( \frac{H}{P} \right)^{0.2} + 13.9 \left( \frac{L}{W} \right)^{0.35} \left( \frac{H}{P} \right)^{0.15} - 14 \left( \frac{L}{W} \right)^{0.35} \left( \frac{H}{P} \right)^{0.2} + 0.094
\]

- The “discharge coefficient” \( C_w \) for the PKW is not approximately a constant - as for the linear weirs - but a function of the upstream head \( H_u \).
- The utilization of such “universal formula” at a preliminary stage of the study may present some difficulties if not correctly applied.
- The different proposed mathematical forms do not allow finding the “optimal economic solution”.
- In fact, the best way for sizing a PKW structure is:
  1. to use “standard models”, existing PKWs and simplified software, in a first approach,
  2. to carry out a first optimization taking into account the structural, construction and economic constraints,
  3. to finalize the design with the results of numerical and/or physical models.
2.2.2 Dissipation of energy downstream the PKW

Several tests have been already carried out for this topic but only for some specific projects.

The general tests performed in Vietnam and in HECE-ULg (Belgium) with a Creager and a PKW installed on the dam crest show a better aeration of the flows on the upper part of the stepped spillway but the calculation of the residual energy at the toe of the dam and the measures of the scour in the stilling basin do not allow drawing now a definite and clear conclusion for the designs. Some further tests seem then necessary.
3. THE NUMERICAL MODELS
Some existing numerical models

- **A simplified 1D-numerical model by HECE-ULg.**
  
  This software is based on a 1D modeling of the inlet and outlet separately, with interactions between both flows.

- **3D models with Flow-3D®.**
  
  This model adapted and developed by EDF was calibrated and validated - for free flows and submerged flows - on the existing physical models.

- **Ansys CFX version 13.**

For all these models, comparison of the numerical results with experimental data has shown their ability to predict the release capacity of a PKW, whatever its geometry, on a significant range of the head in the reservoir.
4. ADVANTAGES OF THE PKW - UTILIZATION
4.1 Main advantage of PKW and labyrinth weir

Main common advantage of the PKWs and the labyrinth weirs compared to an ogee weir: The high specific discharge capacity $q_s$ vs. $H_u$ for $H_u/P < 1$.

[The tests - for PKW and labyrinth weirs - were performed for $H_u/P$ up to 2].

As an additional spillway ($+\Delta q$), a PKW and a labyrinth weir are generally interesting if $H_u/P < 1$ and rarely if $1 < H_u/P < 2$, because even these high heads are hydraulically efficient, they might be uninteresting from an economic point of view as compared to the construction cost of an ogee crest.

If the purpose is to increase the reservoir capacity ($-\Delta H$), a PKW can be interesting even for $H_u/P > 1$.

- Possibility to increase the spillway capacity and/or the active storage of the reservoir with the same dam height.
4.2 Advantages of PKW compared to labyrinth weir *(in general)*

- **Higher specific discharge** $q_{SW}$ (about 8 to 12%): the lower discharge for the labyrinth weirs (with $\alpha > 7^\circ$) can be explained mainly by the collision and nappe interference due to the upstream apex and also by the low flow velocity downstream the vertical walls. The overhangs of the PKW types A to C improve also $q_{SW}$.

- **Best efficiency and sensitivity** for the specific discharge $q_{SW}$ with the submerged flow.

- **Narrow footprint**: with the overhangs, possibility to install a fixed spillway, with high specific discharge $q_{SW}$ on the crest of a gravity dam (or a wall).

  *An additional fixed crest spillway*

- **Great flexibility in the design** thanks to the possible numerous PKW shapes *(with or without overhangs of different sizes and different upstream and/or downstream positions)*.

- **Possible cost savings** *(in this comparison, it is necessary to take into account not only the weir, but also the whole spillway, the chute and the stilling basin)*.
An example of PKW installed on a gravity dam (Malarce - EDF) in order to increase the capacity of the existing dam and gated spillway.

The «standard model» was not used due to the special conditions of the structure and of the site. The economic optimization indicated $n \approx 8.25$ for value of $H_u/P = 0.3$. 
Examples of PKW installed on new gravity dams (Vietnam).

Examples of PKW installed on new gravity dams in Vietnam instead of gated spillway. Use of the «standard model» in a first approach; generally with \( n \approx 5 \) and values of \( 0.5 < \frac{H_u}{P} < 0.8 \). Minimum width for the inlet and outlet keys (about 2.5 m).
4.4 Examples of combination of PKW and radial gates

An attractive solution is to combine radial gates with PKW placed on one or two sides of the structure.

The advantages of this solution are:
- Improvement of the dam safety in case of malfunctioning or jamming of some gates,
- Reduction of maintenance of the gates.
- Possible reduction of investment costs.

For side spillway, PKW can also replace radial gates with the same advantages.

The physical model of the Dakmi 2 dam (Vietnam) ↑

The Van Phong dam under construction (Vietnam) ↓
4.5 A comparison of PKW (types A & D) and labyrinth weir for a low barrage (or a side spillway)

4.5.1 Hydraulic comparison (Same planform for the crest)

For free flows: the rating curve of the PKW type A is the highest but there is not a very great difference with the two other weirs.
For submerged flow: for different values of $H_u$, the “efficiency” ($q_{sub}$ vs. $H_d/H_u$) and the “sensitivity” ($q_{sub}/q_{free}$ vs. $H_d/H_u$) are different according to the type of weir. The PKWs are less sensitive to the variations of $H_u$ than the R.L.

**Efficiency:** $q_{sub}$ vs. $H_d/H_u$ for each weir at several upstream heads $H_u$

**Sensitivity:** $q_{sub}/q_{free}$ vs. $H_d/H_u$ for each weir at several upstream heads $H_u$
The comparison shows that the velocity of the flow downstream the vertical wall of the labyrinth weir (RL) - in the outlet cross section in particular - is lower than for the PKW type A and type D with sloped bottoms. This is probably one (but not the main) of the reasons for the less efficiency of the RL.
4.5.2 Structural comparison

1. Stability of the structure
It depends on the type of foundation (bedrock or alluviums). In case of barrages founded on very weathered rock or a thick alluvium layer, the PKW type D is the only structure capable to withstand the external forces with its only dead weight.

2. Quantities of concrete and reinforcement (per m of spillway)

<table>
<thead>
<tr>
<th></th>
<th>PKW A</th>
<th>PKW D</th>
<th>R.L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete (m³)</td>
<td>24.4</td>
<td>39.4 (25.7 mass concrete or masonry)</td>
<td>20.2</td>
</tr>
<tr>
<td>Steel reinforcement (kg)</td>
<td>616</td>
<td>717</td>
<td>1018</td>
</tr>
<tr>
<td>Formwork (m²)</td>
<td>28.7</td>
<td>38.9</td>
<td>42.3</td>
</tr>
<tr>
<td>Concrete surfacing (no formwork) (m²)</td>
<td>20.4</td>
<td>22.8</td>
<td>12.0</td>
</tr>
</tbody>
</table>

The total cost depends on the relative unit costs of the different items and the construction method. In the general case, for a new project, the choice is between the additional costs for a thick wall crest (footprint) or for the overhangs of the weir.

In general, the choice between the different alternatives depends probably more on structural and economic constraints than on small discrepancies in the hydraulic performance.
5. CONCLUSION - PROSPECT
5.1 Utilization of PKW and perspective of development

- Up to now, for all the projects including a PKW, the main purpose was to minimize $W$ and $B$ - for a given $q_{sw}$ - due to the restricted place. As noted by Anderson: «where the weir footprint is restricted by $B$ and $W$, the discharge characteristics of the PKW are definitely advantageous».

A PKW is then generally the best solution for an additional fixed crest spillway.

The development of PKW in the future is very probable with:

- the upgrading of existing spillways required by the increase of the design flood discharges. The PKWs offer a safe and economic solution, in particular (but not exclusively) for the gravity dams.

- the use of PKW in new dams, as the main spillway or in combination with a gated spillway. This last solution can be a safer alternative if the risk of an underestimation of the design flood, or a possible gate malfunctioning or jamming, is not overlooked.

- To widespread the utilization of PKW, it is necessary to develop further R&D on some particular issues and to collect the return of experience of the PKWs already constructed and operated.
5.2 Further R&D for an extension of PKW worldwide

- **Risk of floating debris**
  Already addressed in some particular cases (logs, ice floes, debris boom) but further tests and studies must be performed concerning this risk near the populated areas, dense forests and cold areas in particular.

- **Aeration downstream the PKW inlets**
  Necessity or not, recommendation and methods.

- **Dissipation of energy downstream PKW**
  As the specific discharges of PKW are much higher and the designs of large spillway presently envisaged, this research is urgently needed.

- **Methods of construction**
  Some new methods of construction may be interesting to test with the Contractors (for example: steel structures for low PKW, prefabricated reinforced concrete PKW units for long and low barrages).
5.3 Some possible new types of spillway with PKW

The goal of the following alternatives is to increase the length of the weir in a restricted place.

- **PK Morning Glory spillway**
  To improve the capacity of existing morning glory spillways: an alternative to the daisy-shape.
  - *Tested for Bage reservoir (France) but not finally adopted* (1)
  - *Under construction: Black Esk reservoir (Scotland, G.B)* (2)

(1) (2)
- **A combination of different types of weir (3)**
  A labyrinth installed on a duckbill spillway (Vietnam 2006). A *PKW* is also possible.

- **Fractal PKW (4)**
  Maybe interesting for weirs requiring significant discharges with very low nappe depths. *Already tested in HECE-ULg (Belgium) but not yet under construction.*
Thank you for your attention!