Design and construction of a labyrinth PKW spillway at Saint-Marc dam, France

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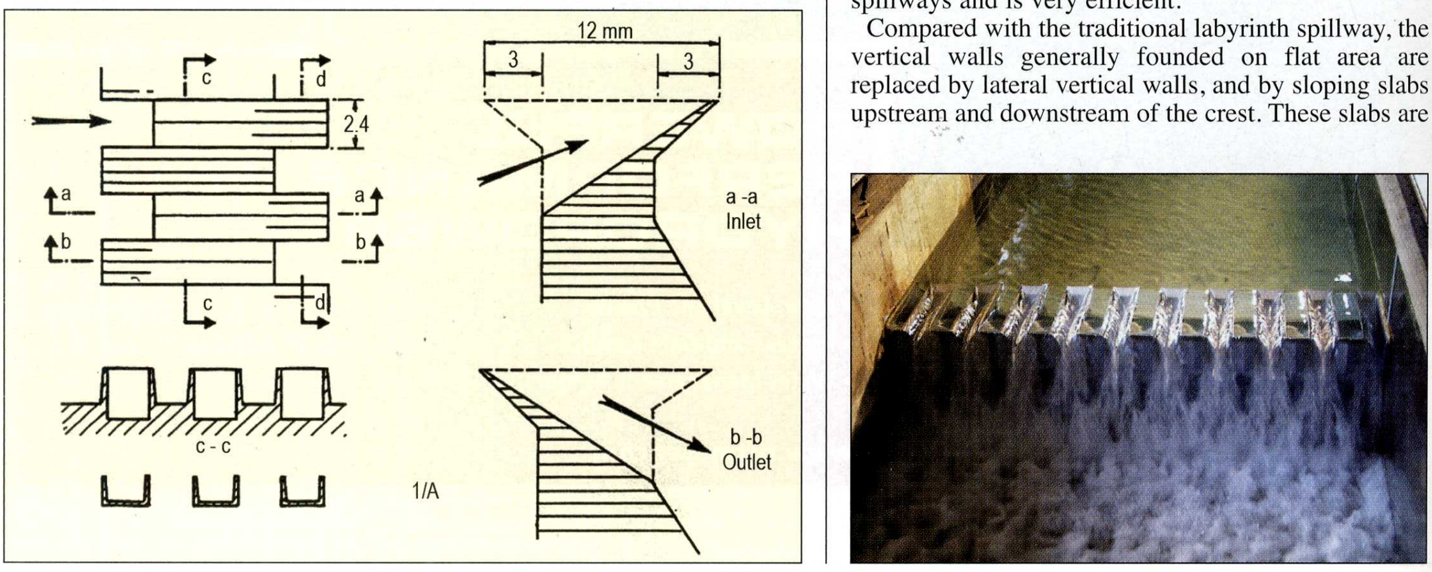
The spillway discharge capacity at the Saint-Marc dam in France was found to be inadequate, when hydrological studies were updated. Following previous experience of a Piano Key Weir spillway which had been installed at the Goulours dam, EDF decided to adopt this concept for the upgrading of flood discharge works at the Saint-Marc dam. The design, including physical model studies, and construction of this scheme are described here.

Piano Key Weir (PKW) labyrinth spillways are a technico-economic optimization of traditional labyrinth weirs. They were recently introduced by Lempérière and Ouamane [2003[1]]. The PKW concept appears to be an interesting option to increase dams discharge capacity by providing high specific flow rates. They can also be used to increase the storage of reservoirs. Unlike traditional labyrinth weirs, PKWs, can be installed on the top of most existing concrete dams [Chi *et al*, 2006[2]; and Ouamane and Lempérière, 2006[3]]. As free-flow spillways, they also provide excellent reliability, and do not require much maintenance. For all these reasons, Electricité de France (EDF) decided to build the first PKW spillway at Goulours dam in 2006. The project was presented in a previous paper by the author [2007[4]].

Because of the good feedback from the Goulours PKW project, EDF decided to launch other such projects, to rehabilitate dams with insufficient discharge capacity, one of which was Saint-Marc dam. Saint-Marc is a 40 m-high concrete gravity dam built between 1926 and 1930. The required additional spillway capacity of the dam, on the Taurion river near Limoges (France) is close to 130 m³/s. A physical model was constructed and operated by the Laboratory of Hydraulic Constructions (LCH) at the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland. Energy dissipation appeared to be a critical problem. It was solved by designing an unconventional 'gutter ski-jump', which routes the water jet into the existing dissipation basin [Leite Ribeiro *et al*, 2009[5]].

Fig. 1. Layout for PK Weir model A according to Lempérière et al., [2003[1]] and (photo, right) original tests at the EDF LNHE laboratory.



In addition to hydraulic issues, both internal and external structural aspects are presented here. Saint-Marc dam is affected by concrete swelling. It was therefore decided not to anchor the PKW to the existing structure, to avoid additional stresses in the new structures. Thus the Saint-Marc PKW simply rests on the existing dam without any physical links. PKW structures are self-balanced with upstream and downstream cantilever slabs. Water loads will bring destabilizing loads, which are moderate compared with gravity stabilizing ones. The Saint-Marc PKW is designed to withstand both earthquakes and ice loads.

The Saint-Marc PKW was finally constructed during the summer of 2008. Works lasted approximately five months, and were within a budget of €1.7 million.

Because good project feedback is now available from both the Goulours and Saint-Marc PKW projects, EDF is continuing to work on other PKW projects, to rehabilitate dams with insufficient discharge capacity [Leite Ribeiro *et al*, 2009[6]]. These should be constructed within a few years.

1. Resumé of the PKW principles

The innovative PKW concept was proposed in 2003 by Lempérière (through the NGO Hydrocoop) and Ouamane (University of Biskra, Algeria). It is not a revolution, but a major evolution of the traditional labyrinth spillway. Because it looked like black and white piano keys when viewed in plan, this new concept was called Piano Key Weir. This design solves most problems which arose with ancient labyrinth spillways and is very efficient.

Compared with the traditional labyrinth spillway, the vertical walls generally founded on flat area are replaced by lateral vertical walls, and by sloping slabs upstream and downstream of the crest. These slabs are partly a cantilever structure both upstream and downstream. Therefore the structure is self-balanced overall.

Unlike traditional labyrinth spillways, the PK Weir can:

- be positioned on top of the crest of new or existing gravity dam (this is the most important improvement introduced by the PKW design);
- allow for a broad range of specific flows, from 3 to 100 m^3/s/ml; and,
- multiply by up to five the specific discharge capacity of the standard Creager spillway, according to the head and the PKW labyrinth ratio and shape.

From a structural point of view, PK Weirs are very hyperstatic, solid and basic structures.

They are also made of simple and straight structural units: They can be precast. Steel or composite materials may be used.

As with a free-flow spillway, PKWs have many advantages compared with gated ones. They are generally:

- simpler to construct; with no mechanical components;
- simpler to operate; with no operator or energy required.
- simpler to maintain; with almost no maintenance required.

They are also safer. The risk of failure is almost non-existent, and floating debris are naturally evacuated. Performance of the PKW against floating debris was explained by Laugier *et al.* [2007[4]]. Most of flow discharged by the PKW does not come from the surface level, but goes through the bottom part of the weir, beneath the surface level. Experimental studies showed that in case of blockage by floating debris, the residual PKW discharge capacity is more than 80 per cent of the nominal one.

In addition, in terms of specific discharge rate, the PKW can compete with gated spillways as the PKW specific discharge rate can reach more than 20 m^3/s/ml for a 2 m head, with an appropriate design.

2. The original Saint-Marc scheme

The Saint-Marc dam was originally constructed with two gated spillways, one 7.5 m wide (gate 3) on the right bank and the other with two passes 10 m wide (gates 1 and 2) at the centre of the dam. Gates 1 and 3 are controlled by an automatic floating device. Fig. 2 shows a schematic plan view of Saint-Marc scheme, the location of the scheme and a downstream view of the dam.

The crest of the spillways is at el. 278.50 m. The normal operating level is at el. 282 m and the maximum operating level is 1.5 m above, at el. 283.5 m.

The 40 m-high Saint-Marc dam creates a 150 ha reservoir, with a retention volume of 20×10^6 m^3. The powerplant is at the toe of the dam, providing 13.5 MW with three Francis turbines.

The first results of physical model tests carried out at LCH (1/30 scale) confirmed that the overall discharge capacity of the three existing spillways is about 623 m^3/s. Based on hydrological studies, a design flood of 750 m^3/s was adopted. The peak discharge capacity is about 130 m^3/s. When taking into account the flood routing capacity of the reservoir, the net discharge capacity is approximately 110 m^3/s.

Saint-Marc dam is affected by concrete swelling. Although the pathology is not as has been developed at other French dams such Chambon or Temple sur Lot, swelling rates are significant and are estimated at between 20 and 40×10^{-6} m/m/year. This affects the choice and design of the new spillway.

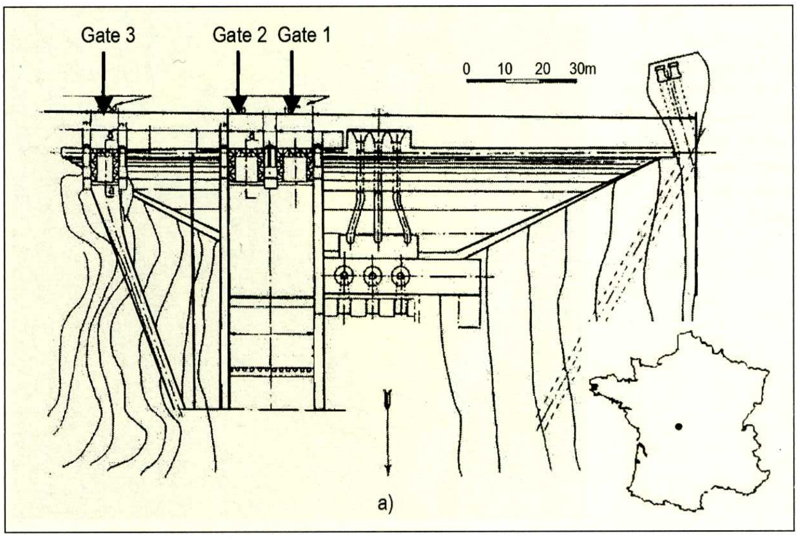


Fig. 2. Schematic plan view of the Saint-Marc scheme in France.

Downstream view of the dam.

3. The Saint-Marc rehabilitation project

3.1 Choice of the design

During the feasibility studies, various types of project were considered to increase the discharge capacity of the dam:

- increasing of the maximum operation level;
- construction of a new larger gated spillway by replacing existing gate 2;
- installation of fusegates or an inflatable rubber gate;
- construction of a free-flow standard Creager spillway; or,
- construction of a free-flow PKW labyrinth spillway.

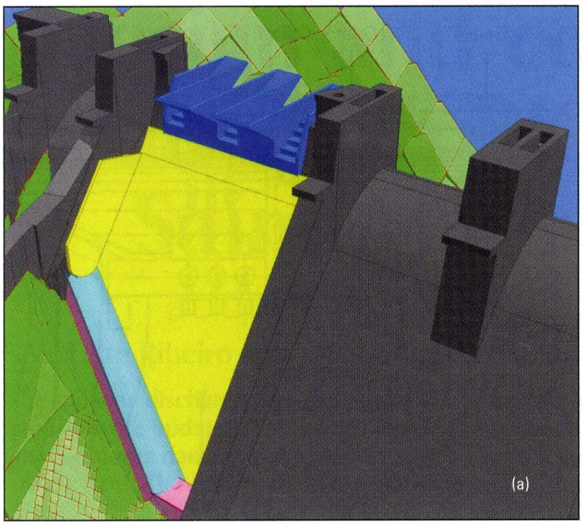
The main constraints to be taken into account were:

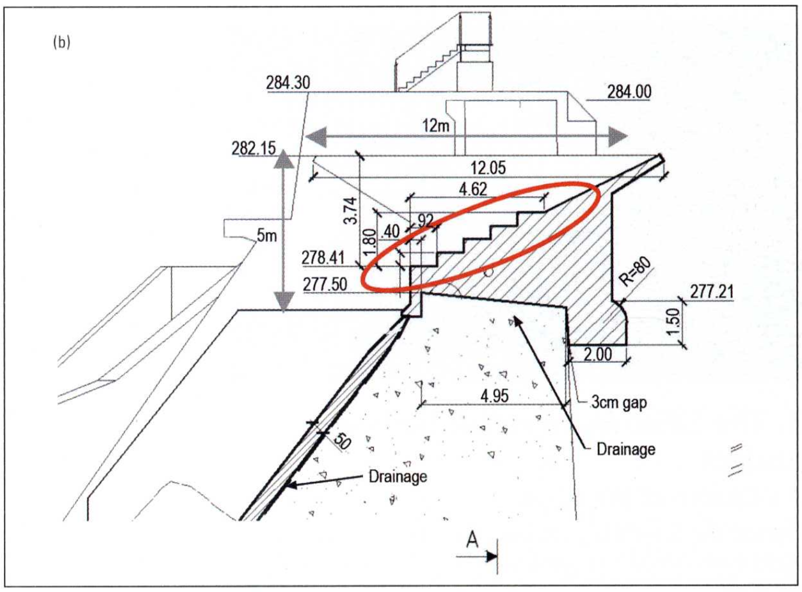
- Lack of available space to install a new spillway. The powerplant is on the left bank. Gate 3 is on the right bank.
- As mentioned before, Saint-Marc dam is affected by concrete swelling. This makes it difficult to anchor a new structure onto the existing one. How to cope with differential displacements creating potential huge stresses in structures? These issues will be addressed later.

Finally when compared with other solutions, the PKW solution was preferred for the following reasons:

- no change of current normal and maximum operating levels;
- no impact on existing gate and other mechanical components;
- reliability of a free-flow spillway, requiring little maintenance;
- low cost of the solution, which involves the construction of simple concrete units; and,
- design of solution fully addressing the concrete swelling phenomenon.

Fig. 3. 3D view of the new PKW spillway, including (a) the downstream face protection slab and the gutter ski jump, and, (b) typical section of PKW outlet.





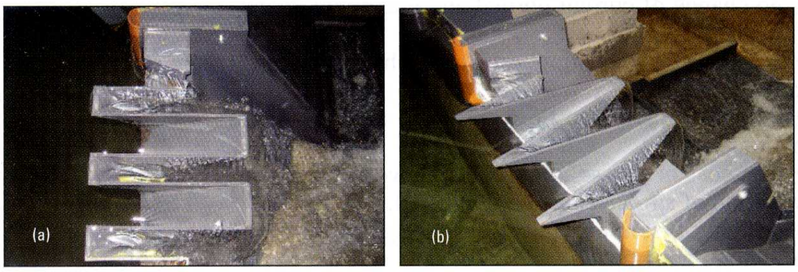
3.2 Description of the new PKW spillway

The labyrinth PKW spillway, as shown in Fig. 3, consists of five alveoli built on 15 ml of dam crest with:

- Two alveoli called 'inlets', approximately 3 m wide, overhanging downstream.
- Three alveoli called 'outlets', approximately 2 m wide, overhanging upstream. They are equipped with steps on their bottom part to improve the energy dissipation and decrease the outcoming water velocity. Steps also improve the flow aeration.

The thickness of the vertical walls is 35 cm. The crest has a semi-circular shape. With this crest shape, the PKW discharge capacity is increased by 3 per cent compared with sharp angles. It also has a better durability and behaviour with respect to floating debris. Upsteam circular deflectors between the inlets improve the incoming flow pattern as per profiled bridges piles. An upstream counterweight has also been added to improve stability, as shown in Fig. 3b.

Upper views of the tested PK Weirs. Rectangular shape (a) and trapezoidal shape (b).



Layout and principal geometrical characteristics of the PKWs studied for the Saint-Marc scheme (see Fig. 4)

	Rectangular PK Weir	Trapezoidal PK Weir
Lt (m)	77.0	68.5
W (m)	15.6	14.4
a (m)	3.45	1.3
b (m)	2.45	0.6
B (m)	12.1	12.9
S_{out} (-)	0.49	0.49
S_{in} (-)	0.49	0.49

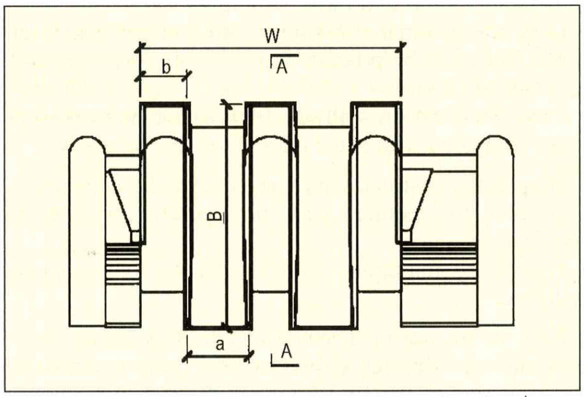


Fig. 4a. Rectangular PKW: situation with flow direction ↓.

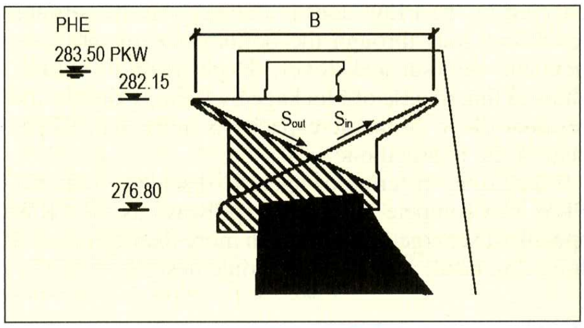


Fig. 4b. Rectangular PKW: A-A cross section.

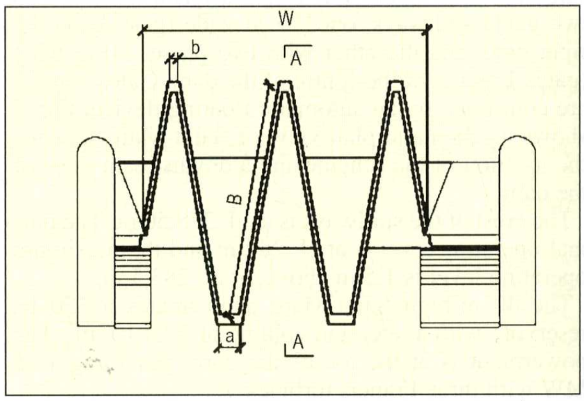


Fig. 4c. Trapezoidal PKW: situation with flow direction ↓.

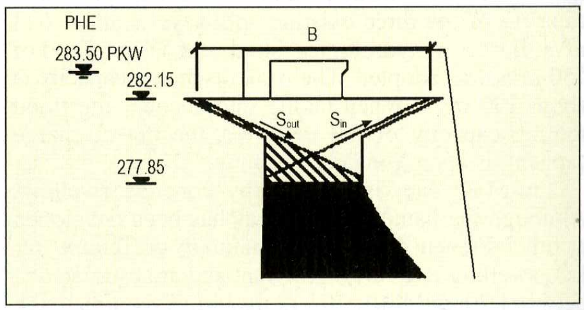


Fig. 4d. Trapezoidal PKW: A-A cross section, outlet alveolus.

In addition to the PKW spillway, the project includes other structures designed to protect downstream structures and improve energy dissipation of the new PKW spillway jet. These are:

• A 50 cm-thick concrete protection slab, resting on the downstream face of the dam.

• A 'gutter ski-jump' built at the boundary between the concrete dam and the existing ground. This non-conventional structure plays two roles: it protects the sensitive area, which is the boundary between the concrete dam and the existing ground; and, as a ski jump dissipator, it diverts the flow from the new PKW spillway. Studies on a physical model showed that the flow is routed to the existing stilling basin without impacting on any additional area.

The hydraulic jump coming from the existing stilling basin downstream of gates 1 and 2 affects a minor unprotected area of existing ground. To protect them, a 30 cm-thick concrete slab is anchored in the ground rock.

The new PKW spillway is installed on the dam crest between gates 2 and 3, where there was enough room. The free-flow crest of the PKW is set at el.282.15 m, which is the normal operating level + 15 cm. Thus the PKW starts to operate when the existing gates are fully open, including gates controlled by an automatic floating device. It corresponds to a 40 year return period event (375 m^3/s), which is larger than the most major historical event which occurred in 1960 (310 m^3/s). This means that the new PKW spillway will not operate for most floods, but only for some rare events. In any case, the existing gates will operate first and their frequency of operation will not change. This option is appropriate for mechanical gates, the components of which should be used as often as possible. Moreover, floating debris will be attracted and discharged by these gates first. The risk of floating debris affecting the PKW is therefore very low.

4. Studies on the physical model

4.1 Setup at LCH

The experimental model of the St-Marc dam, operated with respect to Froude similarity, was constructed at LCH with a geometrical scale factor of 1/30. It simulates approximately 130 m of the reservoir, the dam body, the existing spillways and the designed PK Weir. On the downstream side, the model reproduces the stilling basin of the left spillway, the channel of the right bank spillway and the current topography of the valley. A more detailed description of the experimental facility as well as the measuring instrumentation is provided by Leite Ribeiro *et al* [2007[6]].

In addition to the PKW described above (rectangular shape), another type with a trapezoidal crest shape and the same size alveoli has also been tested at LCH. Both rectangular and trapezoidal shape models are shown in the photos on p102. The Table and Fig. 4 summarize the main geometrical characteristics of these PK Weirss.

4.2 Experimental results

4.2.1 Spillway capacity

Previous situation

Experimental results show that the maximum capacity of the existing spillways at el. 283.5 is 623 m^3/s. This discharge is smaller than the design flood of 750 m^3/s. The capacity of the existing spillways therefore needs to be improved to ensure the safety of the dam.

For the measurements, various gate operations have been considered, and no interaction between the spillways units was detected during the tests, meaning that the maximum capacity can be obtained by totalling the individual capacities.

PK Weir

The PKW with a rectangular shape as presented in Fig. 4a has a maximum capacity of 134 m^3/s at el. 283.5, while the trapezoidal shape (Fig. 4b) has a capacity of 112 m^3/s. This difference results essentially from the total developed crest length, which is almost 8 m less for the trapezoidal shape (68.5 m) compared with the rectangular one (77 m). Based on the required capacity, the rectangular shape was adopted for the St-Marc dam rehabilitation.

The adjustment of the rating curves for the tested PKW was based on the classical Equation (1) for linear crest spillways, as presented by Bieri *et al* [2009[7]]:

$$Q = C_d L_{eff} \sqrt{2g} H^{\frac{3}{2}}$$

The PKW can be considered as a linear crest weir with an effective length (L_{eff}) decreasing with the increase of the head (H). The variation of L_{eff} related to H can be adjusted with a function f(x)=1/xn. Thus, using the magnification aspect L_{eff}/W, Eq. (2) is proposed to fit the variation of L_{eff}.

$$\frac{L_{eff}}{W} = 1 + \frac{1}{\left(\frac{H}{W} + \frac{1}{\sqrt[n]{\frac{L_t}{W} - 1}} \right)^n}$$

Using Eq. (2), Eq. (1) can be written as:

$$\frac{Q}{W} = C_d \frac{L_{eff}}{W} \sqrt{2g} H^{\frac{3}{2}}$$

The discharge coefficient C_d was assumed for a sharp-crested weir over the total developed length of the PKW. This value has been set constant, at 0.42. To adjust the capacity curves for the PKW, the coefficient n (Eq. 2) has been set as 7.5 for the rectangular shape, and 7.8 for the trapezoidal shape. The discharge capacity curves for the PKW studied, as well as the total discharge capacity curve for the rectangular PKW and the existing spillways, are shown in Fig. 5.

The total measured discharge at maximum operating level with the PKW corresponds to the total of the present capacity, and that of the adopted PKW (623 + 134 = 757 m^3/s). This is slightly higher than the peak value of the design flood of 750 m^3/s.

4.2.2 Energy dissipation

Concerning the energy dissipation of the flow discharged from the PKW, various solutions have been proposed and analysed on the model.

The first option was to protect the natural gneiss between the existing spillways, and to evacuate the water jet to this region. This, however, is not appropriate from the energy dissipation point of view, as the structure of right bank channel could be severely affected by the flow.

Another option consisted of three ski jumps, with lateral deflectors placed at different elevations, with a view to guiding the flow into the stilling basin of the left spillway. This gave satisfactory results in terms of energy dissipation. To reduce the impact of the jet on the downstream face of the dam, however, the highest ski jump would have to be placed downwards. For this configuration. a considerable excavation volume would have to be taken in account.

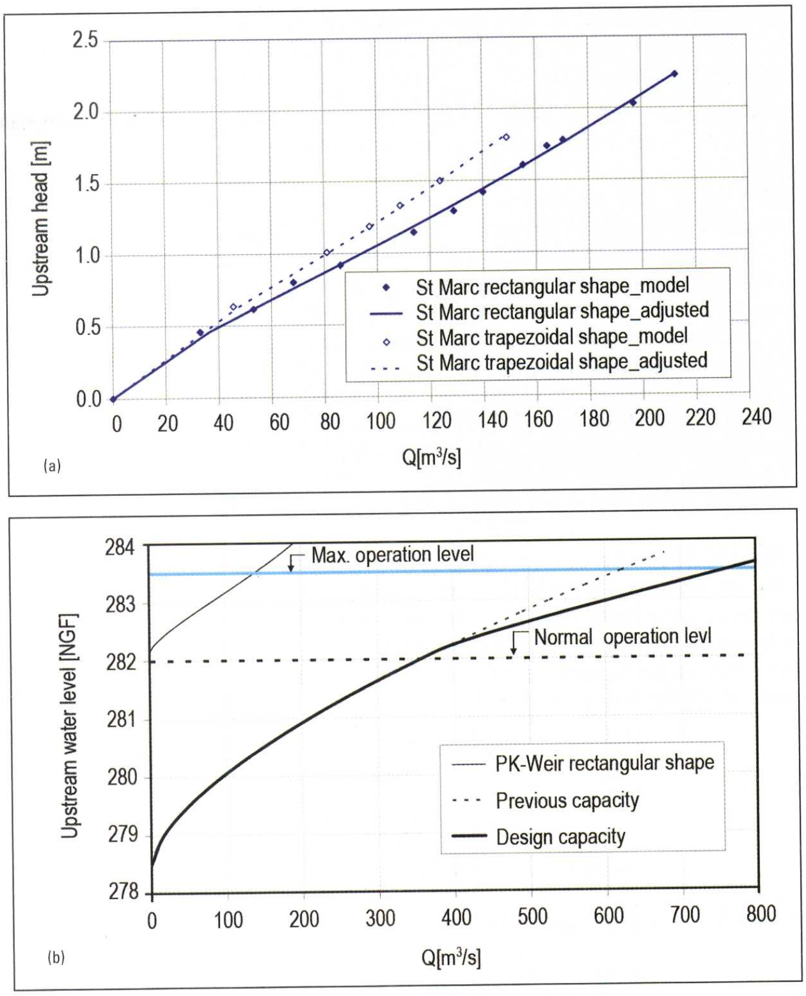


Fig. 5. Discharge capacity curves for (a) the PKW studied, and (b) the designed capacity curve for the Saint-Marc's dam considering the PKW with the rectangular shape.

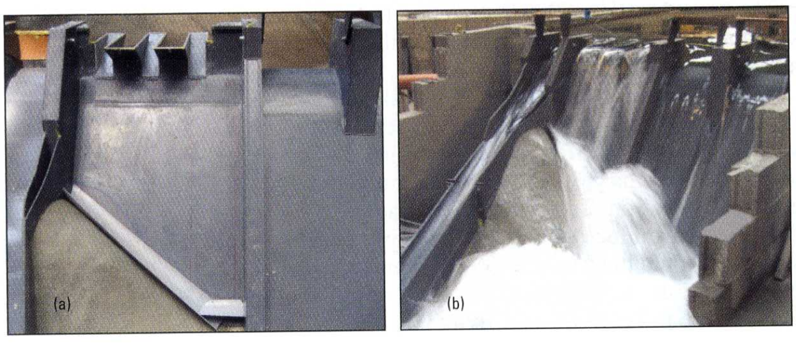
The solution adopted is a leaning 'ski-jump gutter' placed at the contact line between the downstream face of the dam and the natural rock, as shown in photo (a) below. The gutter consists of a cylindrical profile with a constant diameter placed after along an inclined axis with a horizontal reach at the downstream end of the structure. The aim of this solution is to guide the flow from the PKW to the stilling basin of the left existing spillway, as shown in photo (b) below.

To improve energy dissipation and to mitigate impact length of the flow on the downstream face of the dam, additional measures have been taken at the outlets of the PKW. They have been quite efficient in improving the performance of the ski-jump gutter.

4.2.3 Pressure measurements

To analyse the behaviour of the energy dissipating structure downstream of the PKW, pressure measurements have been taken at various locations on the structure. An electronic transducer with a precision within more than 0.1 mm and a sampling frequency of 100 Hz was used.

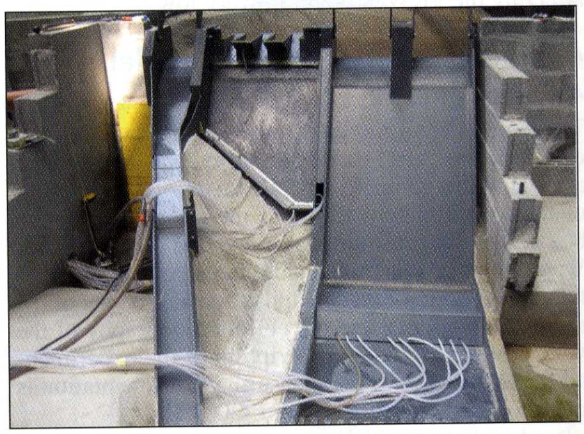
Downstream views of the St-Marc model with (a) the PKW and the gutter out of operation; and (b) the gutter during the transit of the design flood.



Measurements were taken in the inlet of the PKW, on the downstream face of the dam, in the gutter, on the right guide wall of the left spillway and in the stilling basin, as shown in the photo below. The signal registered was subjected to a classical statistical analysis, including the energy spectrum density and the distribution function curve.

The following comments can be made, based on these measurements:

- *Upstream alveolus of the PKW*: Vibrations occur on the structure with 0.8 Hz frequencies at prototype scale, if the jet is not aerated. These vibrations disappear with complete aeration of the under nappe of the jet.
- *Downstream face of the dam*: Mean pressure values from 0 to 2 m water column (w.c.) and maximum standard deviation value of 0.5 m w.c. at the point with the maximum mean value.
- *Inclined gutter*: Mean pressure values from 3.2 to 8.5 m w.c. and a maximum standard deviation 1.1 m w.c. For this structure, theoretical calculations were done with the approximate radius of the flow-lines (which are in fact elliptic as shown in the lower photo, and differ significantly from the measured pressures, except for the horizontal part. This behaviour can be partly explained by the evaluation of the specific flow, which is not uniform; but it seems that the assimilation with a classical ski jump with a constant equivalent radius is not applicable in this case.
- *Right guide wall of the left spillway*: Mean pressure values lie close to zero. This means that no collision will occur between the jet coming from the inclined gutter and the wall. The standard deviation varies from 0.30 to 0.5 m w.c.
- *Stilling basin of the left spillway*: Pressure measurements have been compared between the existing situation and the project design. Results show that the



Downstream view of the model with the dynamic measuring points.

Flow-lines trajectory in the gutter.

PKW will not lead to significant variations of the mean values and standard deviations for most points. The most relevant difference is observed in the shaded zone of the pier dividing the two existing passes. At this location, pressure values are actually close to 0 m w.c. and will increase to 2.5 m w.c. with the PKW.

5. Structural design

5.1 External stability: concrete swelling

The mechanical design of the new structures was strongly influenced by the concrete swelling that affects Saint-Marc dam. The swelling rate is estimated at between 20 and 40 mm/m/year. Any fixed mechanical link between existing and new structures might therefore imply the development of significant confinement stresses between the new structure, made of non-swelling new concrete, and the existing structure which has been affected by swelling. Traction forces would be applied to the new structures as well as shear forces at the interface between both structures.

Two types of solutions are possible to ensure the stability of new structures:

• *Fastening of the new structure*: For this type of solution, it is necessary to:

(i) design the new structure taking into account stresses created by the dam displacements over a given time period;
(ii) provide suitable shear resistance required by anchors; and,
(iii) check that the stresses that are induced in the dam are acceptable.

• *Detaching the new structure*: The new structure will not be anchored so that stresses would be transmitted to the existing dam by gravity load. Stresses which are induced in the new structures by swelling are limited by the shear resistance provided by the friction capacity at the interface.

The fastening solution is the most usual one when anchoring a new structure onto an existing one. Calculations were carried out based on a 50 year lifetime. They led to significant technical issues which seemed difficult to address:

• What is the durability of anchor sealing in swelling concrete? How will the swelling affect the bonding properties between the various components? Modelling such an issue is not easy, and the technical literature does not provide many answers.
• Fine assessment of the swelling rate is a difficult issue, as well as the assessment of actual stresses induced in the structures by swelling. It would require extensive monitoring of the dam to assess swelling displacements of a minimum number of points. It would also be necessary to perform complex 3D structural analysis, including complex time-dependant concrete swelling law. Therefore, it is recommended to consider rather conservative design hypotheses, which can lead to expensive over-design.
• Anchoring units work permanently, as most stresses are caused by swelling.
• It is necessary to use high strength steel anchors which are more sensitive to stress corrosion.
• The design is undoubtedly characterized by a limited lifetime.

Although it appears to be unusual for this type of project, a system based on strength by gravity load seems to be feasible in this case, without requiring a huge quantity of concrete. This solution was therefore chosen to ensure the stability of the new PKW spillway on the Saint-Marc dam. This solution was also chosen for appurtenant structures on the dam, such as the dam downstream face-protecting slab, and the ski-jump gutter. In other words, news structures simply rest on the existing dam. Following this principle, the new PKW is designed against extreme floods, ice loading (30 cm-thick ice layer) and earthquake.

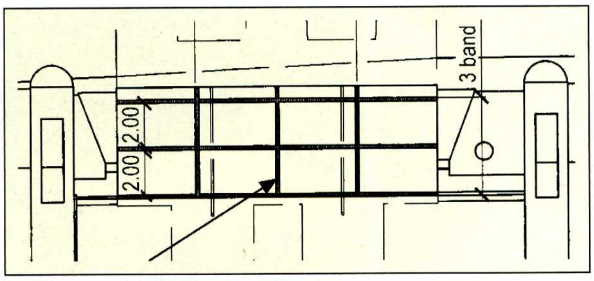


Fig. 6. Drainage principle between PKW and dam.

Ice loading appears to be a critical aspect for the internal design of the PKW, in terms of reinforcement. PKWs, are thin structures, and could even have been called Accordion Weirs. They are therefore sensitive to lateral loading from ice, which is 5 t/ml worth for a 30 cm thickness. Walls 35 cm thick are required to withstand ice adequately. The reinforcement ratio does not exceed 80 to 120 kg/m^3 in the most critical areas.

The Saint Marc site is not a seismic area. The ground design acceleration is only 0.1 g. However, the PKW is located at the top of the dam, so, amplification of the ground acceleration leads to 0.4 g design earthquake.

To ensure appropriate detachment of the new PKW and the existing dam, a 3 cm free gap is left between both, as shown in Fig. 7. This gap is sufficient to allow for the dam swelling for more than 50 years. The reduction of the gap can easily be monitored in the future. An additional stability safety measure is provided by the PKW upstream concrete beam, the elevation of which is beneath the dam excavation level. The primary function of the beam is to bring additional weight to the PKW, which works as a gravity structure. In addition, it is capable of providing significant shear resistance to prevent from PKW sliding.

5.2 Waterproofing and drainage

5.2.1 PKW spillway

The waterproofing system between the dam and the PKW is a triple system; comprising the following:

• a waterstop joint along the perimeter interface between dam and new PKW;
• a waterproofing membrane on the dams upstream face, overlapping the PKW; and,
• a sealant in the upstream 3 cm of free space between the dam and the PKW.

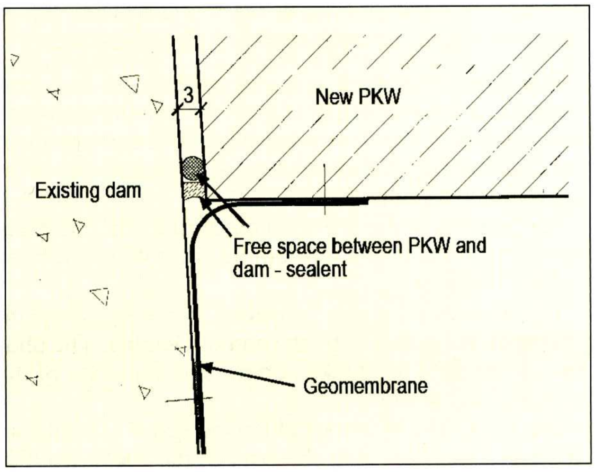
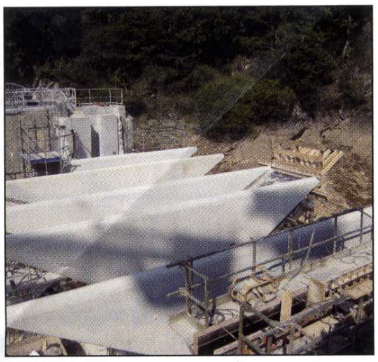


Fig. 7. Waterproofing principle between PKW and dam upstream face.



Construction under way at the Saint-Marc PKW and (a, b) vertical walls and (c) the ski jump gutter.

In case of failure, leakage will be collected by a drainage system at the interface between the existing dam and the new PKW, to release uplift pressure. This consists of a grid of voids which allows for evacuation downstream through the existing pendulum borehole.

5.2.2 Aeration

To aerate the flow on the PKW, two air intakes (400 mm in diameter) have been implemented.

Both structures start below the downstream alveoli and exit on to the dam crest on both sides of the PK Weir. They will be protected by stainless steel covers and connected to each other to allow redundancy of air supply in case of blockage of one pipe.

6. Construction

Construction works were done during the summer of 2008 from May to October. The overall schedule was tight because of various factors such as:

- Other works planned at the same time for Saint-Marc dam, including the installation of a geomembrane on the upstream face and other maintenance works.
- The requirement to maintain a high reservoir level for as long as late as possible to ensure water supply until mid July.
- The requirement to finish by the end of October, before the start of the flood season.
- Works in parallel, both at the top and at the toe of the dam, requiring some specific safety measures.

The dam demolition was not as easy as foreseen, because of the varying quality of the existing concrete construction joints. It was therefore necessary to adapt the final position of excavation according to the actual position of joints.

The photos above were taken during the construction. They underline difficulties of these acrobatic works at height.

The work was finished on time, and the powerplant was back in operation by the end of October. The photos on the right were taken after the completion of the construction works.

The final cost of work did not exceed €1.7 million. It should be noted that the cost of the PKW itself is less than one-third of the total amount. Two-thirds of the total amount correspond to:

- site access and installations fees; and,
- construction of energy dissipation structures works, such as the concrete protection slab for the downstream face of the dam and the ski-jump gutter.

This lesson appears to be very common for spillway rehabilitation works. Issues such as energy dissipation, access, installation and works methodology are often more significant than the spillway itself. ◊

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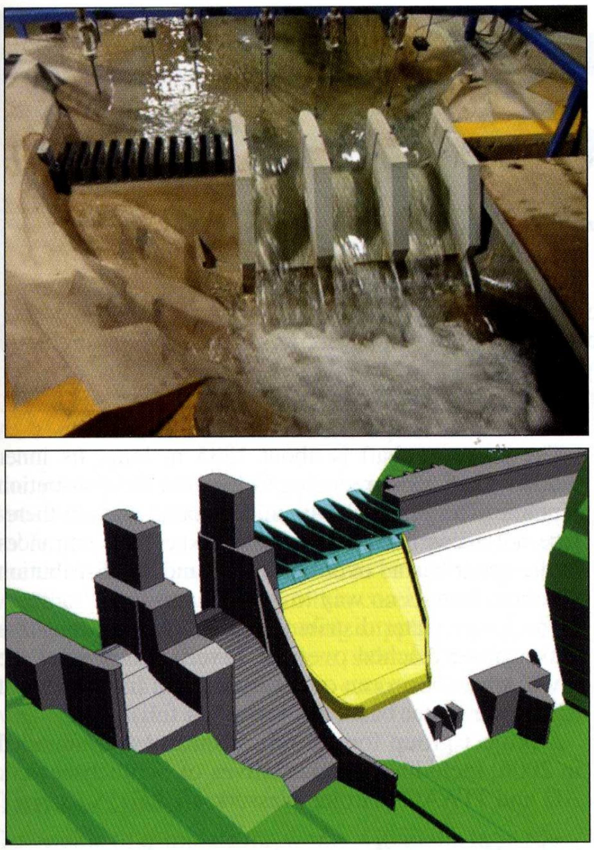
Downstream views of the St-Marc dam after the achievement of the works.



Current EDF PK Weir projects at (a) Malarce dam and (b) L'Etroit dam.

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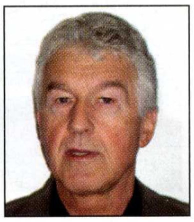
A. Lochu

C. Gille

M.L. Ribeiro



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