Innovative spillways

PK-weirs . Franska exempel

10/04/2018

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CEO

Chairman of ICOLD Technical Committee on “Emerging Challenges and Solutions” (2013-2018)

10 years ago…

ISL Engineering office, FRANCE,

www.isl.fr

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Innovative spillways : Why and where we stand?

- **ICOLD TECHNICAL COMMITTEES database**

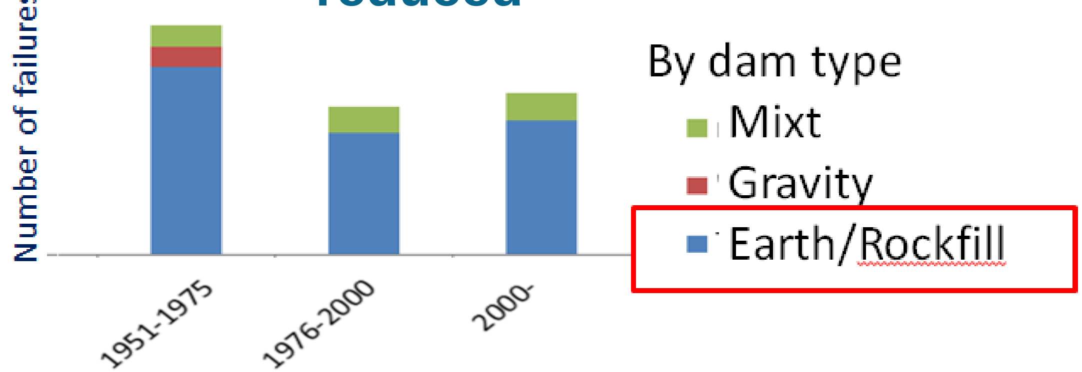
Spillways are the #1 issue for dam safety

Last 25 years : 1990 – 2015 : 1,000 fatalities from 24 dam accidents

70% of which related to floods and spillways

Figures improved a lot during the twentieth century, but could still be reduced

•by overtopping

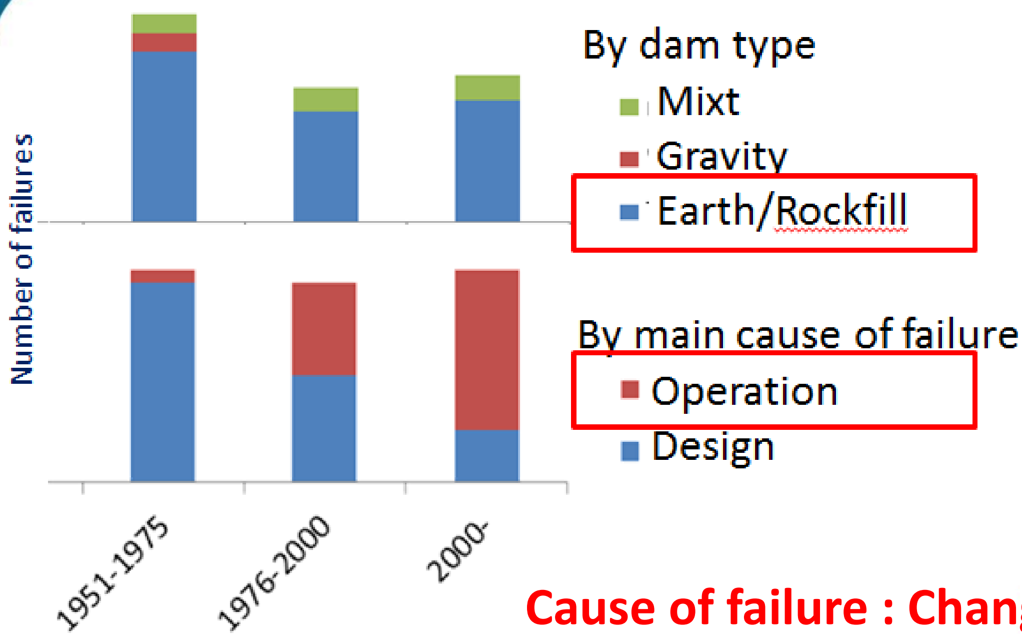


Lessons learned from dams failures due to spillways operation

Florent BACCHUS[1], Luc DEROO[2], François LEMPERIERE[3], Michel POUPART[4]

•French team ([1])

Innovative spillways : Why and where we stand?



FLOOD EVALUATION

AND DAM SAFETY

ICOLD B170

More stringent standards regarding design floods have been the key to this shift

Cause of failure : Change of the trend :

Past failures : often due to (1) an undersized Safety Design Flood ; (2 – lesser extend) to structural and hydraulic lack of design

Recent failures : The operation of spillways and especially the operation of gated spillways is now the first cause of dam failures.

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Innovative spillways – How ?

Back-analysis of these past accidents - performed by a French team ([1]) and focused on French large dams.

5 tricks to increase spillway safety

1- Concrete dams: improve safety during unexpected overtopping

Internal workshop on overflowing of dams and dikes - > 12/2017 – Overtopping certainly possible but still need engineering improvement to be justify in dam design

2- Gated spillways: develop standards for PLC (control-command)

Major cause for inappropriate manoeuvring of spillway gates; no technical standard on how to design, test and maintain these key components for dams

Upstream operational safety / downstream operational safety – Compromise

3- Flood operation rules: an assessment in terms of time factor

Balance between the flood kinetics and the timeframe required for the gate operation sequence, including the handling of operation incidents.

4- "Safe & sound" design incorporating at least 2 safety barriers

5- Warning & evacuation: updated methods using mobile phones

→ *spillway design*

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Innovative spillways – How ?

Among the solutions: innovative spillways

- That **would not fail to operate** as expected during the flood event – whatever the conditions for energy, access and floods
- That **would not unexpectedly open** causing harm to people in the riverbed downstream
- That provide generous **safety margins to handle hydrological uncertainties** - between MWL and dam crest

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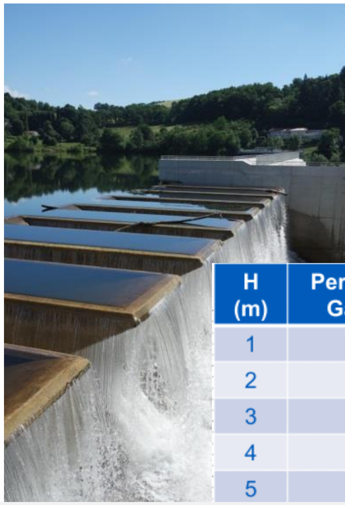
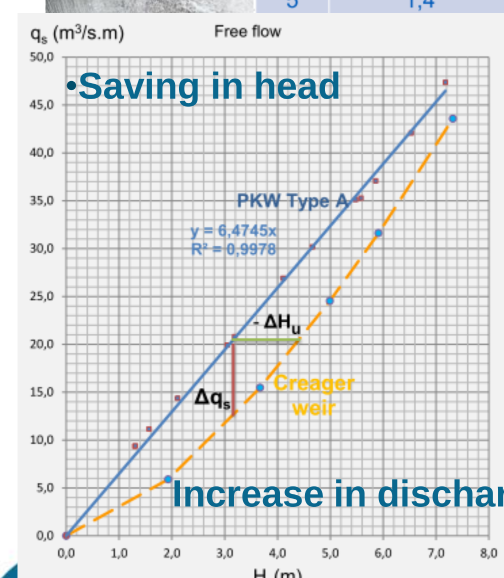
Among the solutions : PK-Weir - Design

Pkweirs (invented by F. Lempérière): a new standard, that proves universal, well world-spread by EDF.



H (m)	Performance Gain ratio
1	3,8
2	2,6
3	2,2
4	1,6
5	1,4



- **PKW is much more efficient than an ogee crested weir of same width, especially for low heads : 2 to 5 times greater than an ogee crest using the same width – large impact on flood routing**
- **variation of the traditional labyrinth weirs with ramped floors ; + 15% of discharge**
- **can replace gates in various circumstances - avoid safety issues associated to them**
- **strong hydrological safety : a flood much higher than the design flood can be spilled with a limited upstream water elevation**

archetypal feature of “safe design barrier”

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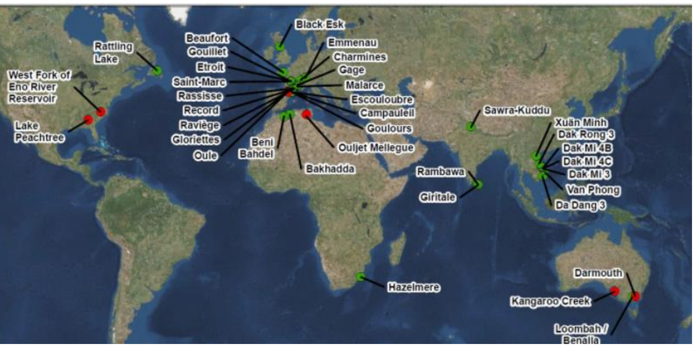
Among the solutions : PK-Weir

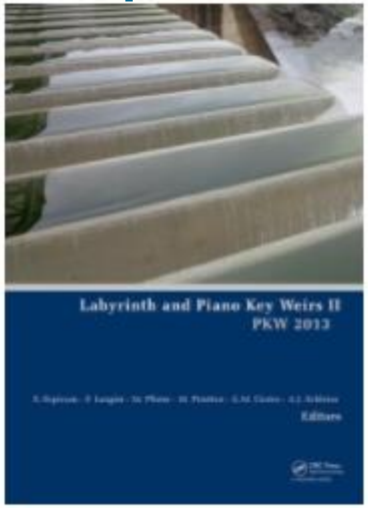
- http://www.pk-weirs.ulg.ac.be
- 3 proceedings

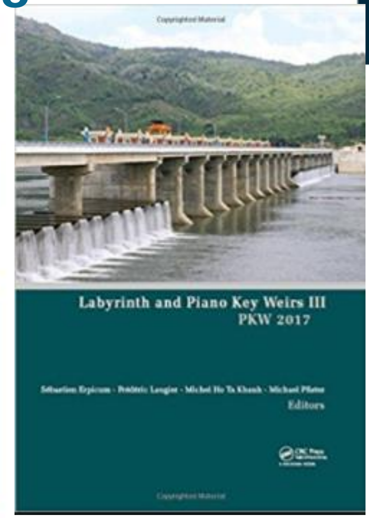
ICOLD – TECHNICAL COMMITTEE ON HYDRAULICS FOR DAMS
CIGB – COMITÉ TECHNIQUE SUR L'HYDRAULIQUE DES BARRAGES

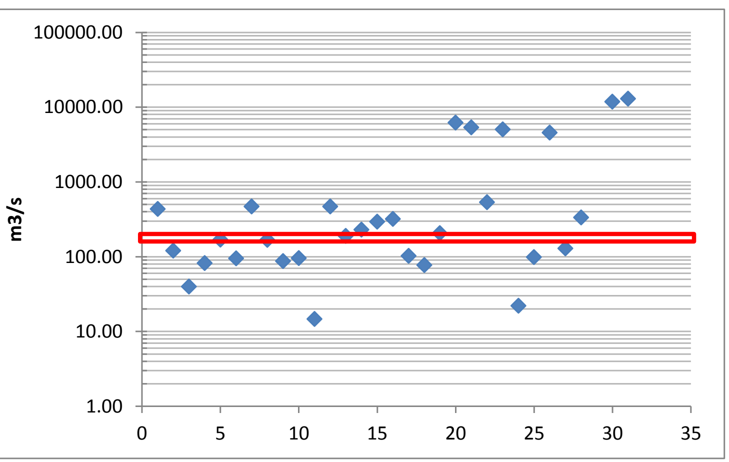
ICOLD B172

TECHNICAL ADVANCEMENTS IN SPILLWAY DESIGN
Progress and Innovations from 1985 to 2015









- World Register of PKW (~30 – ISL : 5)

Estimation of A-type Piano Key weir rating curve

Michael Pfister & Anton J. Schleiss
Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH - 1015 Lausanne, Switzerland

2 main technical papers

Experimental parametric study and design of Piano Key Weirs

Olivier Machiels Project Engineer[a], Michel Pirotton (IAHR Member), Professor[b], Archambeau Pierre Research Associate[c], Benjamin Dewals (IAHR Member), Assistant Professor[d] & Sébastien Erpicum (IAHR Member), Research Associate[e]

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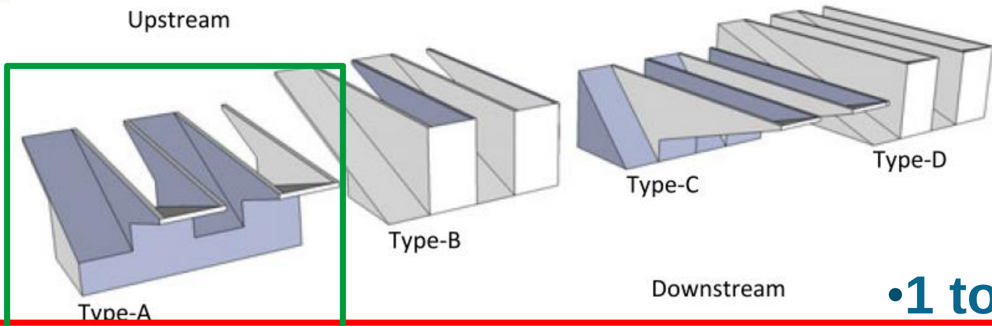
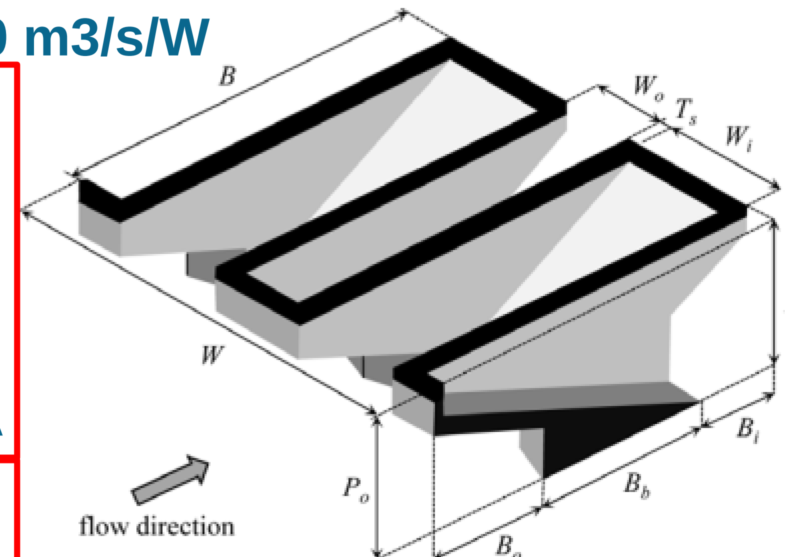
Among the solutions : PK-Weir - Design

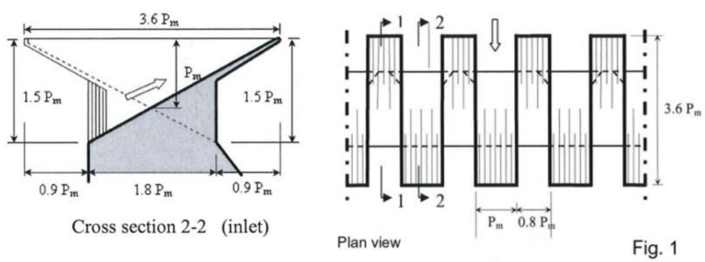


Naming convention for the Piano Key Weirs geometrical parameters (Pralong et al. 2011)

Figure 6.4 - Types of PK weir (adapted from Erpicum *et al.* 2013b)

- **1 to 90 m3/s/W**





$$q = 4{,}3\sqrt{P_m}\,H$$

Feasability study : Lempériere easy to use formulae – PKWA

Detailled design – several optimisation (5-10%) well documented

- **inlet/outlet key width (better incoming flow “feeding” in inlet keys ,**
- **Wall thickness,**
- **Crest shape**
- **Upstream pier shape**
-

Pfister et al., Lausanne, 2013

Machiels et al., Liège, 2014

Caution to input parameters that change

In case of spillway upgrade, caution should be taken to the face height that will impact the dam stability

Ingénierie

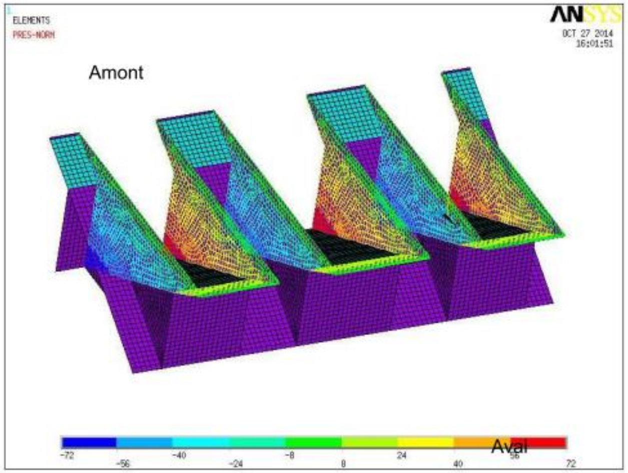
Among the solutions : PK-Weir - Construction

•**Structural design :**

-> No more sensitive than Labyrinth : vertical walls height is reduced as well as the volume of reinforcing steel required in concrete (re-inforcement : 90-110 kg/m3 ; formwork : 100-130 m²/W 1.3 à 1.5 m²/m³)

-> Thin structure (less than labyrinth) but hyperstatic and stiff

-> Outlet key on banks in order to limit loads on channel sidewalls



Attention to controling sizing parameters :

- **Thermal load (Eurocode thermal load)**
- **Ice loading (when applicable – detailled later)**
- **Impact load (Eurocode $F_{max} = V\sqrt{KM}$:)**
- **Particular attention to seismic loading (crest)**

Among the solutions : PK-Weir - Construction

-> Well adapted to pre-cast element (full key, half key, only walls)

- **project constraints : dissipation, access, installation, operation, floods...**

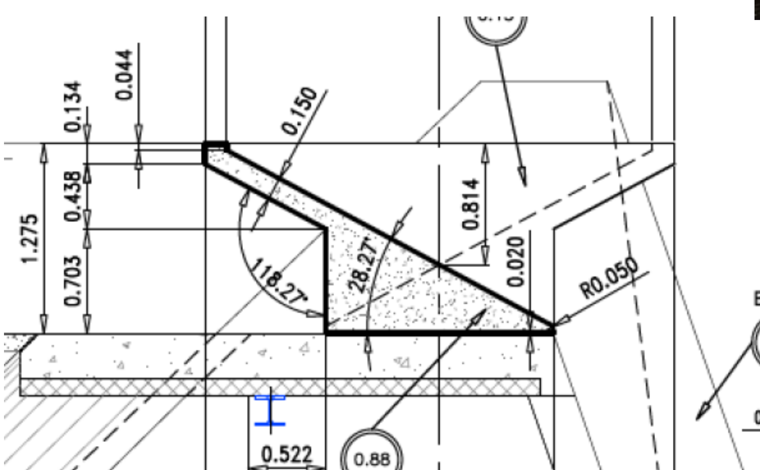
Rassisse-ISL

Beaufort

Among the solutions : PK-Weir – In-situ results

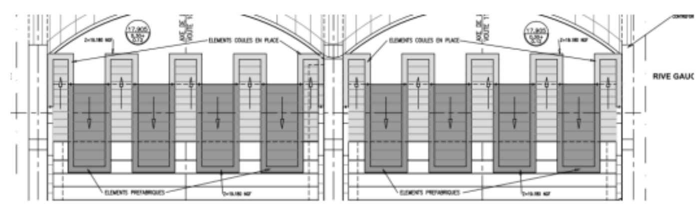
-> Can be implemented on each type of dam

Beaufort-ISL



Ingénierie

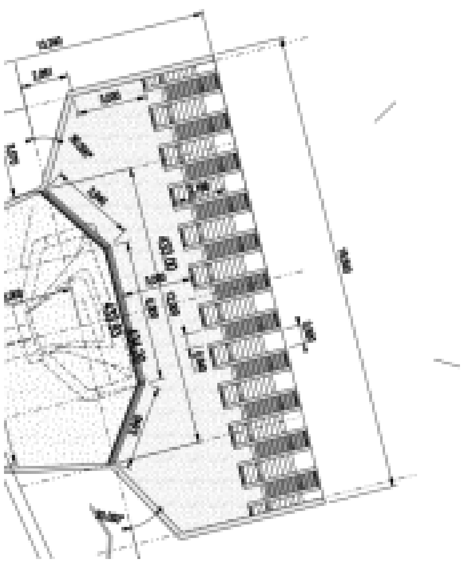
PKW discharge capacity at MWL (m3/s):	76
W (m):	14.99



Plan view of the PKW

Among the solutions : PK-Weir – In-situ results

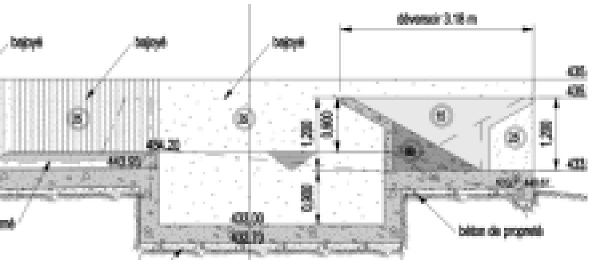
-> Can be implemented on each type of dam



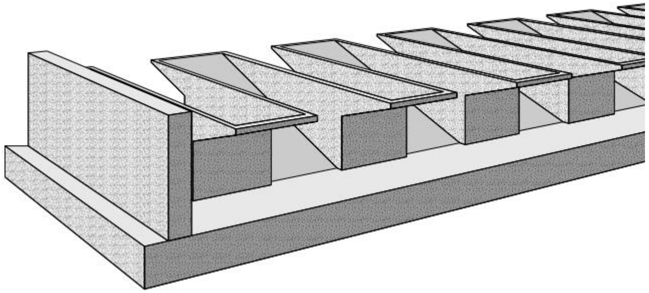
Plan view of the PKW

Gouillet

PKW discharge capacity at MWL (m3/s):	18.2
W (m):	19.14

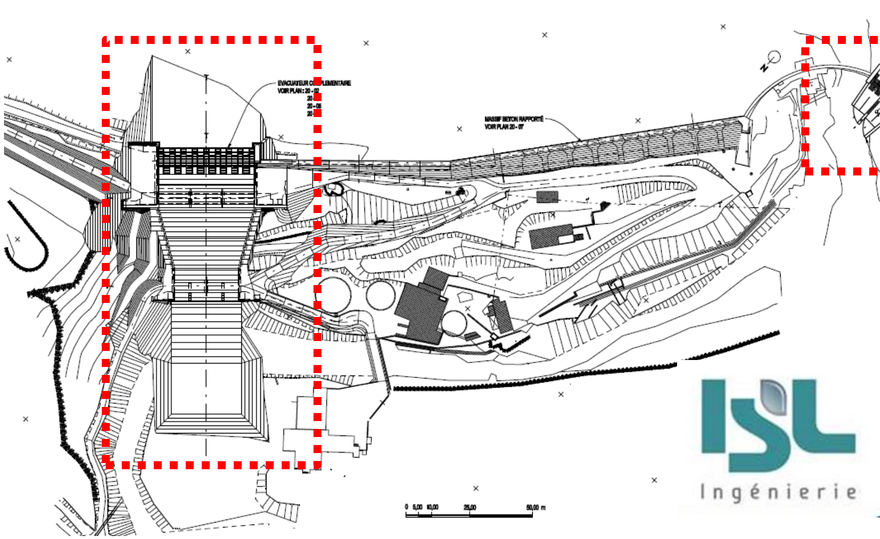


Cross-section view of the PKW



Among the solutions : PK-Weir – In-situ results

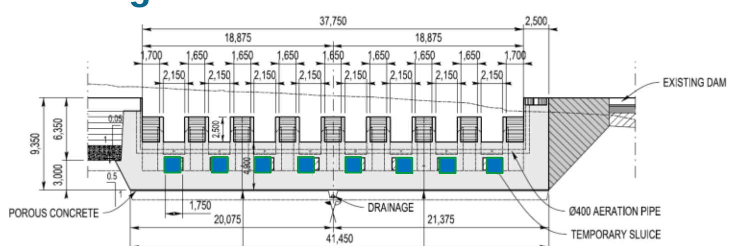
-> Can be implemented on each type of dam

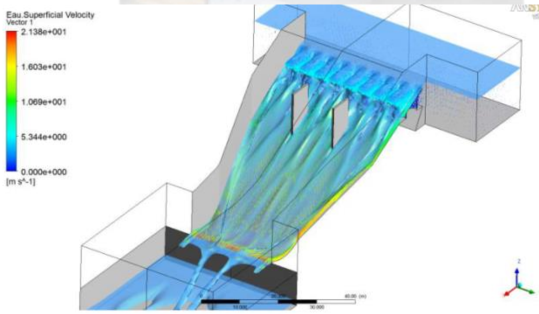


Mise en service des pertuis provisoires (photo du 04/03/2015)

Rassisse1-ISL

Opportunities to include temporary sluice under the keys for work flood management on existing dam

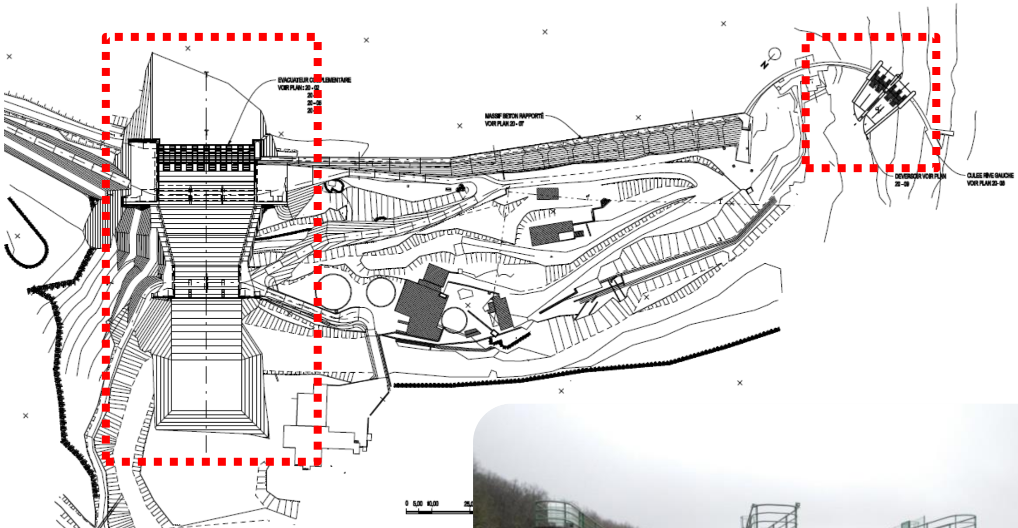




PKW discharge capacity at MWL (m3/s):	PKW1 : 306 PKW2 :101
W (m):	PKW1 : 37.75 / PKW2 :14

Among the solutions : PK-Weir - Résults

-> Can be implemented on each type of dam



Rassisse2-ISL

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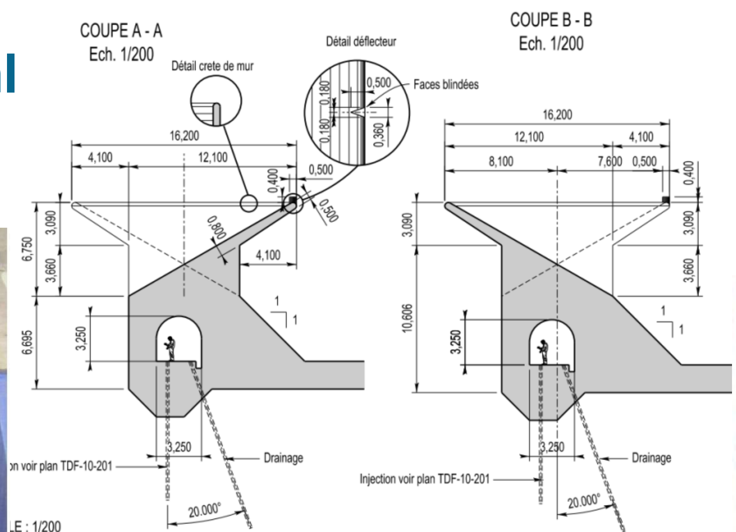
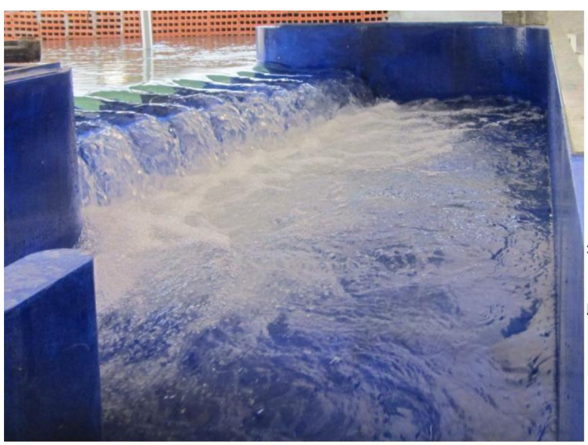
Among the solutions : PK-Weir – In-situ results

- **4500 m3/s – 50 m3/s/ml**
- **W= 90.5 m**

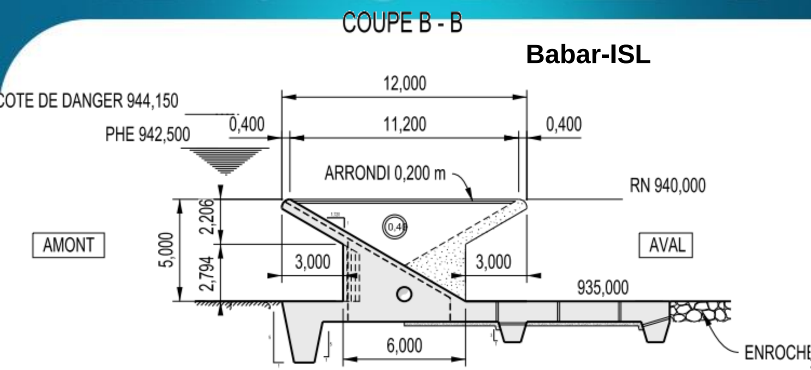




Ramdane-ISL

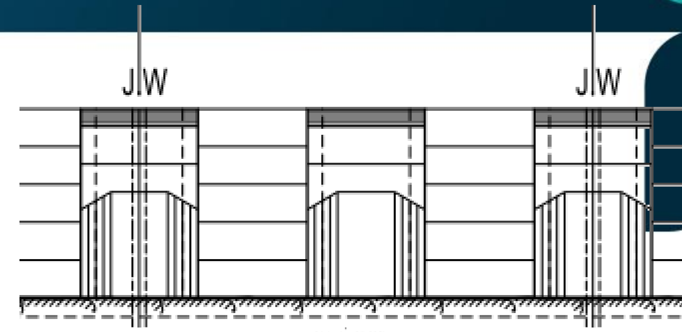
SCOTLAND

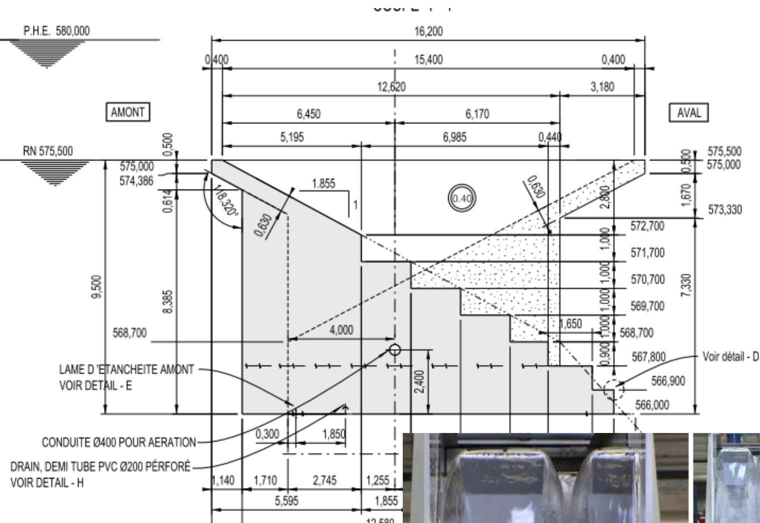
Among the solutions : PK-Weir - Résults



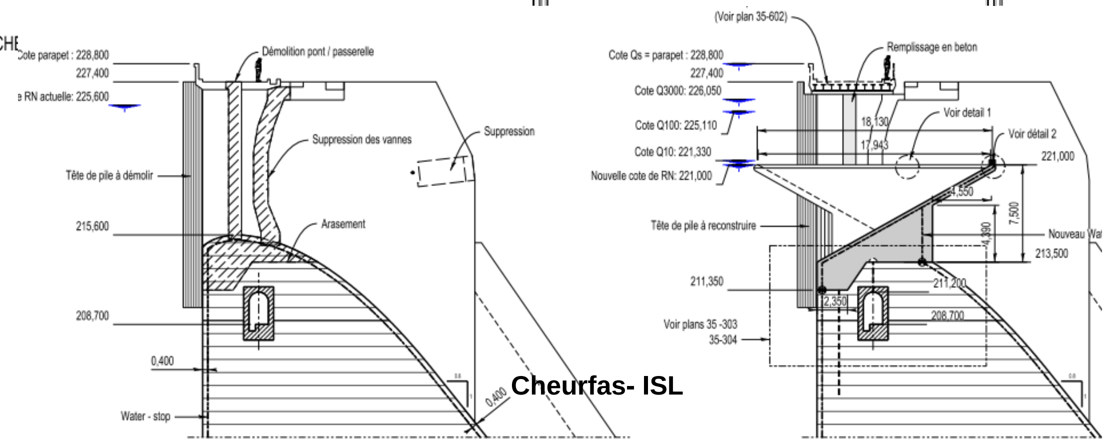
Babar-ISL

- **Pier shaped and downstream submergence**



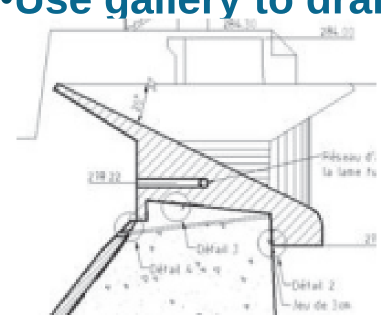


Ouljet Mellegue - ISL



Cheurfas- ISL

- **Use gallery to drain – Anchors to stability**



- **Stepped outlet key for dissipation**

Ensure stability by upstream counterweight

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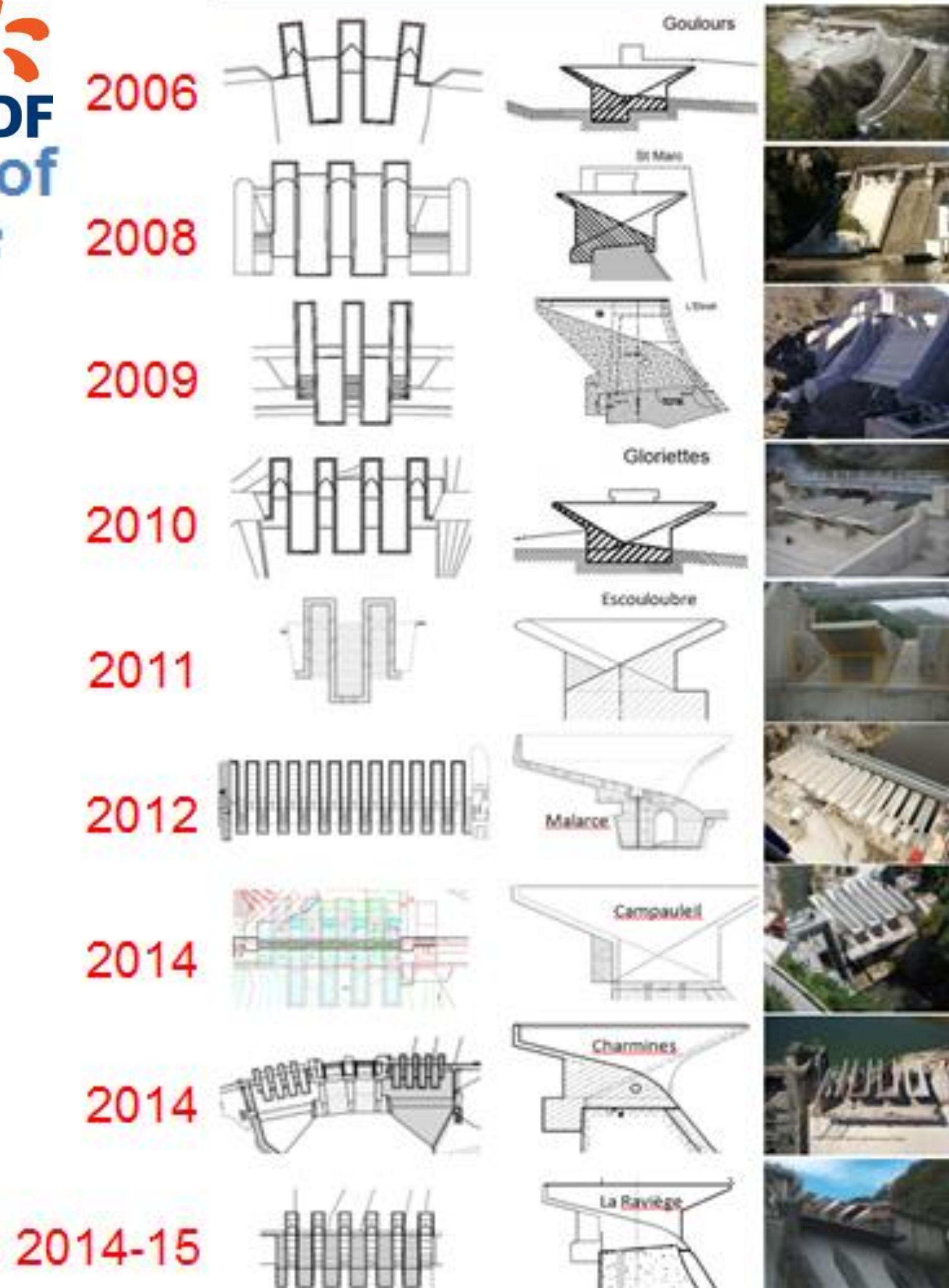
Plan and cross-section of 9 first PKW built by EDF

	Goulours	St Marc	Etroit	Gloriettes	Escoul.	Malarce	Campauleil	Charmines	Raviège	Gage
Dam type	Concrete gravity	Concrete gravity	Concrete gravity	Slim arched	Concrete gravity	Concrete gravity	Concrete gravity	Cc gravity and earth	Concrete gravity	Slim arched
H on ground level (m)	20	40	25	43	13.4	28.4	15.8	17	37	39.6
Dam's date of construction	1946	1932	1933	1951	1971	1968	1939	1948	1958	1954
PKW's date of construction	2006	2008	2009	2010	2011	2012	2014	2015	2014-15	2015-16
PKW localization	Bank	Dam crest	Dam crest	Bank	Bank	Dam crest	Dam crest	Dam crest	Dam crest	Bank
Dam design flowed (m^3/s)	162	660	500	150	13	4600	192	685	1700	675
Q PKW at MWL (m^3/s)	68	138	82	90	13	570	120	300	300	455
q_{sw} at H = 1 m ($m^3/s/m$)	5	6.5	9	6.8	~ 4(2)	9.4	8.3	8	8.5	11
Total project cost (k€)	400	1800	1500	1600	615	4500	2800	6500	4000–5000	15000–20000
PKW Cost (k€)	300	400	400	400	230	800	450	1800	1000–1200	900–1300
Head on PKW at MWL (1) (m)	0.95	1.35	0.95	0.8	0.65	1.5	0.9	1	1.4	1.75
Cconstruction (month)	3	6	6	5 (1)	6	12	6	6	6	
B (m)	9.3	12.7	12.2	10	5.1	13.46	13.1	13.24	13.24	13
B_o (m)	3.35	4	3.2	3.5	1.2	6.63	4.9	3.97	4	4
B_i (m)	1.5	4	2	2.6	1.2	2.03	2.8	4.41	3.33	3
B_b (m)	4.4	4.7	7	3.6	2.7	4.8	3.5	4.87	5.91	6
P (m)	3.1	4.2	5.3	3	1.8	4.4	5.35	4.38	4.67	6
W (m)	12	18	18.7	18.5	4.8	42.5	16.55	2*23	25.8	26.6
W_i (m)	2.7	3.1	5	2.3~2.5	1.3	5	1.55	2.4	2.4	1.6
W_o (m)	1.5~1.8	2.2	1.5	1.5	0.9	1.58	1.4	1.6	1.65	1.3
T_s (m)	0.2	0.25	0.35	5	0.3	0.2~0.4	0.35	0.35	0.25~0.4	0.25~0.4
L (m)	59	77	78	86.8	22	350	115	2*120	177	208
P_{pr} (m)	0	0	0.5	0	0	1.65	0.7	1	1	0.8
B_s (m)	1	1.5	1	1.5	1	1.5	1	1.15	2	2
Nose form	triang.	triang.	triang.	round	triang. extruded	triang.	triang.	round	triang.	triang.



French Guidelines

•Dams are classified into 4 ranks A B C D depending on V at NWL and total Height $H^2\sqrt{V}$

•No PAR/LOSS classification as dams in France are in sensitive areas

•Safety design flood

	Rigid dams	Loose material dams
A	1000 to 3000	10,000
B	1000	3000
C	300	1000
D with V ≥ 50,000 m³	100	300

Table 4.6 – Return periods for floods in exceptional situations

•Check flood

Dam class	Annual exceedance probability
A[10]	10^{-5}
B	3.10^{-5}
C	10^{-4}
D with V ≥ 50,000 m³	10^{-3}

$\alpha * Q_{10000}$

- Several hydrological approach : rainfall-runoff transformation processes (GR4; Gradex;…)

- Determination of the occurrence of safety check floods using the incremental damages method

•http://www.barrages-cfbr.eu

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French Guidelines - Floatings

Jamming is assessed taken into account :

- the intrinsic sensitivity of the watershed (to the production of floating debris – Altitude, land cover,…);
- the intrinsic sensitivity of the reservoir (reservoir configuration, use wind direction, Vflood/Vreservoir);
- spillway sensitivity (shape, protection systems);
- spillway design (span, overhead clearance, water height etc).

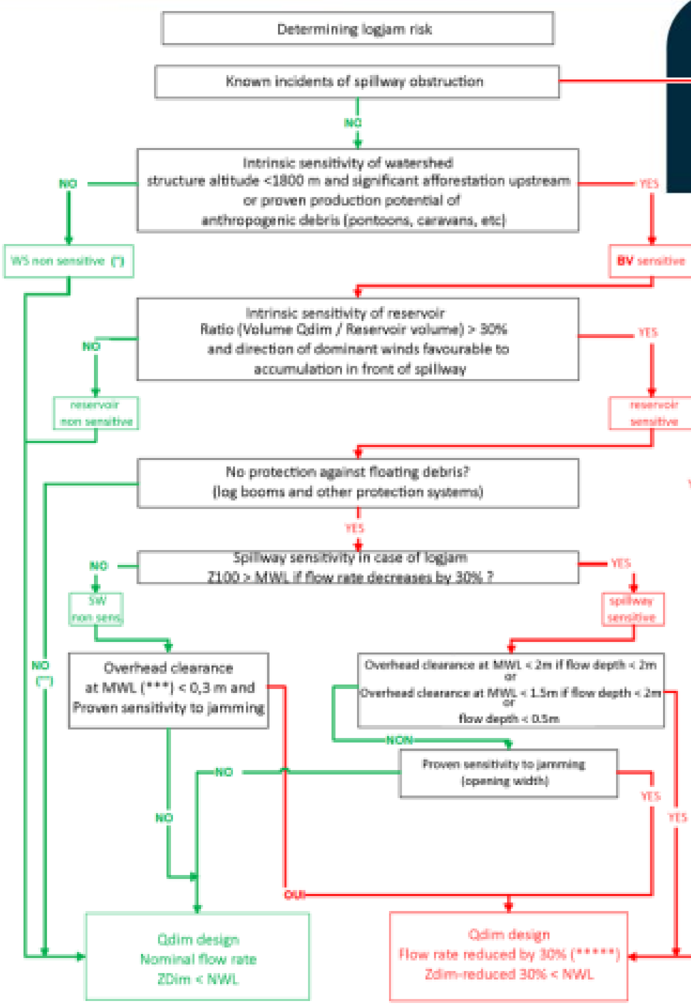

Figure 3.8 – Logigram showing determination of logjam risk

•If sensitive – jamming checked flood Q100 with decrease discharge (30 to 50%)

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French Guidelines - Floatings

Positive PKW behavior against floating debris blockage risk

Well studied by

EDF

- **@Laugier,EDF**
- **For Rehabilitation projects, general comments :**

⇒ Generally other existing spillways, often gated one with high specific flows – Attracts debris

⇒ Gates generally operated first for medium floods (often until 100 years Return period)

⇒ As freeflow spillways, <u>debris will pass when water head increases</u>

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French Guidelines – Ice load

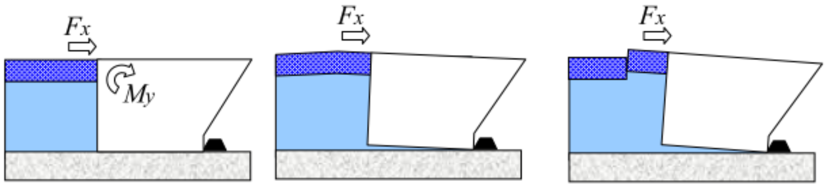
- **Ice thickness estimate : ROSA 2000**

$$I_g = |\Sigma T_m| \text{ avec } T_m < 0$$

$$Z = A \cdot \sqrt{I_g}$$

- **With A :2.2 to 2.6**
- **Often 30 cm, even more**

- **Pressure according to DIN : 150 kg/m²**
- **BUT :**
  - **It is assessed if ice can occur with NWL / flood (normally not – management guideline in case of maintenance…)**
  - **The deformability (bending of the sidewall) of the structure will limit the load**



Du fait de son expansion thermique, la glace pousse la hausse fusible.

Si cet effort devient suffisamment fort, la hausse commence à pivoter autour de ces butées. Auquel cas, la couche de glace fléchit.

Pour un angle de rotation donné (0,5° a 1,0°); la couche de glace casse et la hausse revient en place.

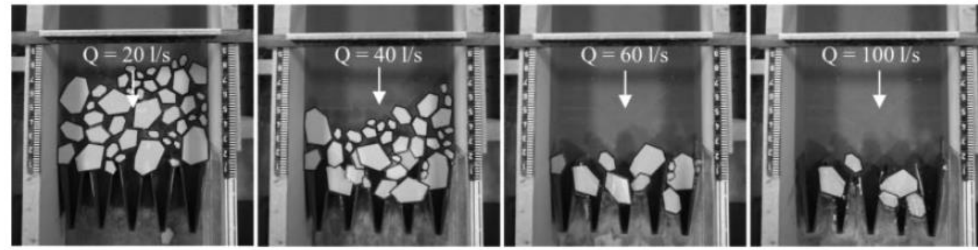
en 2001.

Hausses fusibles sur le barrage de Khorobrovksaya

French Guidelines – Ice load

A comparison of side weirs and labyrinth weirs at Ilmenau river

M. Gebhardt, J. Merkel, F. Belzner & C. Thorenz
Federal Waterways Engineering and Research Institute (BAW), Germany



5.3 *Accumulation of ice*

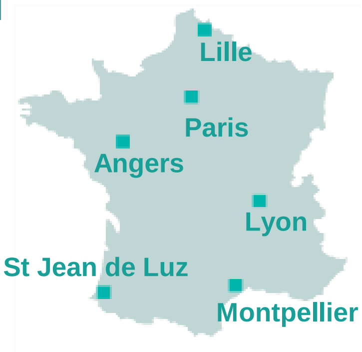
Ice is an issue in cold climates. On one hand the pressure causes an additional load (Falvey, 2003), on the other hand it is also problematic if floating ice gets stuck in the keys and reduces the discharge capacity. In ongoing investigations a trapezoidal and a rectangular labyrinth weir are also compared with regard to the accumulation of ice at the weir in dependence of the discharge, ice concentrations and ice shapes (Herbst, 2016). First observations indicate that the increase of the upstream water level is small and floating ice passes the weir with increasing discharge. Only few ice floes remained on the crest of the weir (Fig. 9).

- **Same behaviour than for floatings debris**

Ingénierie

ISL business card

France



// FRANCE

Paris
Lyon
Montpellier
Angers
St Jean de Luz
Lille

// INTERNATIONAL

Tunisia
Algeria
Cameroon
Ivory Coast
Pacific
Belgium
Spain

Inter

Identity

Establishing : 1986 – **30 years**

100% employee-owned

45% International activity – mainly in Africa

10% growth

100 full-time staff members

6 international subsidiaries

3 sisters companies

BCN hydro renewables

// Turbines, Auxiliary Equipment

WATERPOWER ingénierie

// Hydromecanical

DN&T Design Naval & Transports

// Maritime and naval

Thanks for Your Attention

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