Recent large dimensions flap gate on Seine River

by

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ABSTRACT

Recently, 3 weirs with very large flap gates have been re-built on the Seine River near Paris for VNF-DTBS (*Voies Navigables de France*- Seine Basin): Chatou, downstream of and Le Coudray and Vives-Eaux upstream of Paris. The previous weirs had been built about 80 years ago to increase navigation depth on Seine river. They had lift gates (Chatou) or wicket « Aubert » gates.
The flap gates operated each by 2 hydraulic cylinders are remarkable because they are out of or just at the limit of the proven optimal scope of flap gates compared to other types, according to 2006 PIANC report (design of movables weirs and storm barriers), because of the torsional rigidity limit, or out of the range indicated by standard design guide for flap gates made by VNF-Cerema in 2009. There is no example of both larger and higher flap gate. Their main dimensions are spans around 30 m and a water height from 4.8 to 7.8 m.
However, the reasons why this kind of gates has been chosen are mainly aesthetic, liability, precise regulation and price.
The main design, construction or operating constraints have been the structure, the energy dissipation basin, the cofferdam, the maintenance bulkhead, and fish passes.
The flap gate design will be compared: use of torsion tube or traditional fish belly shape, design and installation of hinges and cardan joint. The large gates have been installed in several parts assembled on place with bolts. The hydraulic cylinders' rods have unusual long strokes, 9.25 m for Chatou weir.
For Le Coudray Weir, a laboratory physical model (scale 1/12) has been made and improved the calculations and design, for discharge, hydrodynamic forces, energy dissipation basin, hydraulic jump and downstream protection, aeration and vibrations prevention.
The hydraulic winter conditions imposed to be able to remove the cofferdam every winter. In addition the soil conditions were difficult: hard limestone or chalk. So, innovative sheet-piles cofferdams have been made: cofferdam without concrete plug in Chatou, sheet-piles set on riverbed with bored piles and injections in rock in Le Coudray to insure stability and watertighting.
For the 3 weirs, the maintenance upstream bulkhead will be floating ones which led to some difficulties in design and operations, because of the large dimensions.

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1. INTRODUCTION

Three weirs with very large flap gates have been built on the Seine River near Paris for VNF-DTBS (*Voies Navigables de France*- Seine Basin): Chatou, 2nd weir downstream of Paris finished in 2013, Le Coudray finished in 2012, and Vives-Eaux finished in 2017, 4th and 5th weirs upstream of Paris. They are remarkable because they are out of or just at the limit of the proven optimal range of flap gates compared to other types like radial gates or lift gates.

The article will focus on specific points of these three works:

- cofferdam and foundations on rock soil
- design of the flap gate and actuators
- hydraulic design of structure
- floating maintenance bulkheads

The 3 old weirs had been built about 80 years ago to increase navigation depth on Seine river. They had lift gates (Chatou) or wicket « Aubert » gates and had been made to replace XIXth century needles gates. « Aubert » gates called after the inventor, have metallic wickets maneuvered by mechanical arm on a carriage moving on a passway several meters above the weir. They have been used in France in the thirties for 6 or 7 weirs including Suresnes weir holding Paris reach. New weirs have been constructed downstream of the former (Chatou and Vives Eaux) or upstream for Le Coudray.

figure 1 - Chatou previous weir - lift gates

figure 2 - Le Coudray Aubert gate

Flap gates have been chosen for several mains reasons:

- feedback on a lot of smaller flap gates on Seine basin, last 20 years
- probably less expensive
- aesthetic: the superstructures are less visible; this point has been very important for Chatou gate because the old lift gate had an industrial aspect no longer desired for the new one
- liability and precise water level regulation

Nevertheless, especially for Chatou, the dimensions were until now considered as just at the limit or out of the range of flap gates. The span are indeed significant as they exceed 30 m with head from 5 to almost 8 m. Until now, it seems that there are no flap gates both larger and higher than the Chatou one: see Erbisti (design of hydraulic gates 2004).

Several types of gates are classically adapted to these dimensions, as radial gates and lifting gates, or even more recently inflatable gates). For the Chatou dimensions, other types of gates were previously regarded as preferable. However, there is no really prohibitive criterion in spite of smaller flap gates resistance to torsional effort.

2006 PIANC report (design of movables weirs and storm barriers), indicated a preferable span range from 1 to 35 m with 2 hydraulic cylinders and a water height from 2 to 5 m with a limit of 7 m because of the torsional rigidity limit. Similarly, the standard design guide for flap gates made by VNF-Cerema in 2009 gave a upper limit of 4 m for the optimal range. Moreover it recommended a fish belly structure for high flap gate.

New weirs project figures

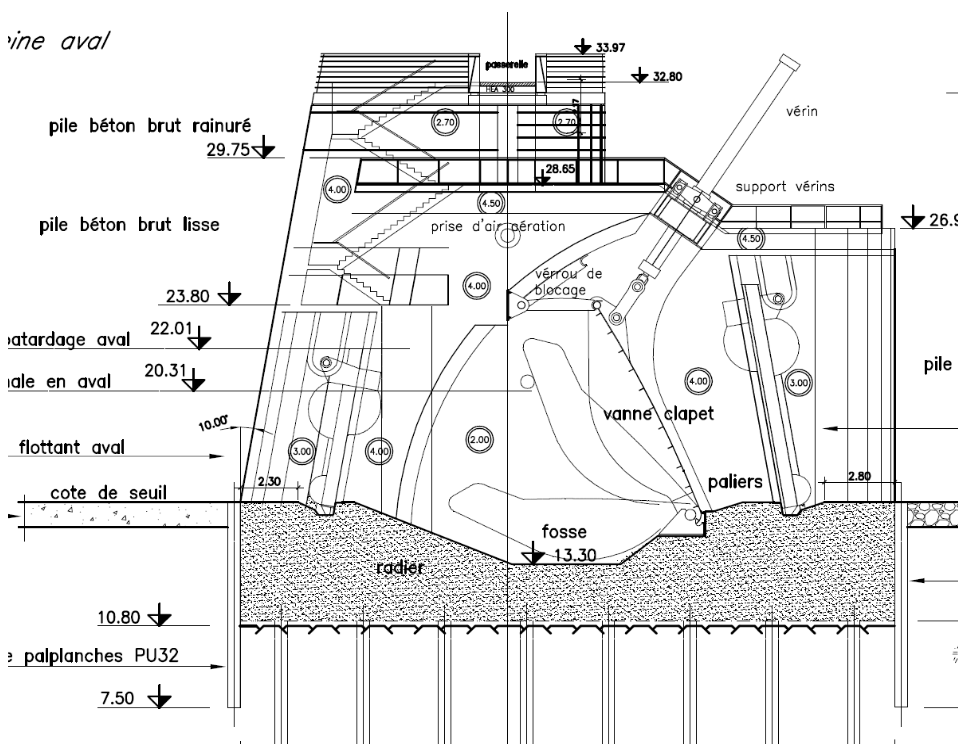


figure 3 - Chatou weir

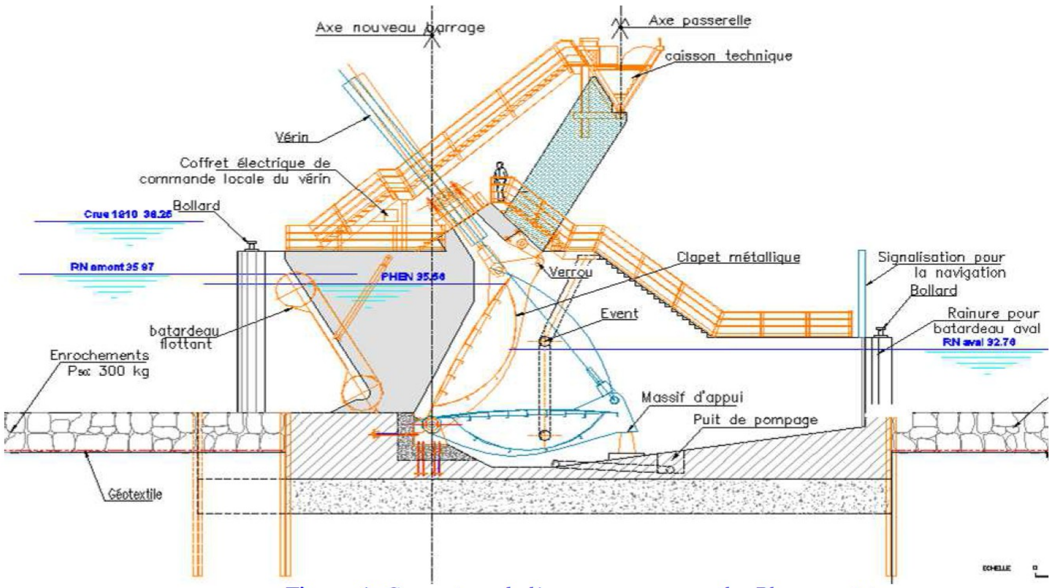


figure 4 - Le Coudray

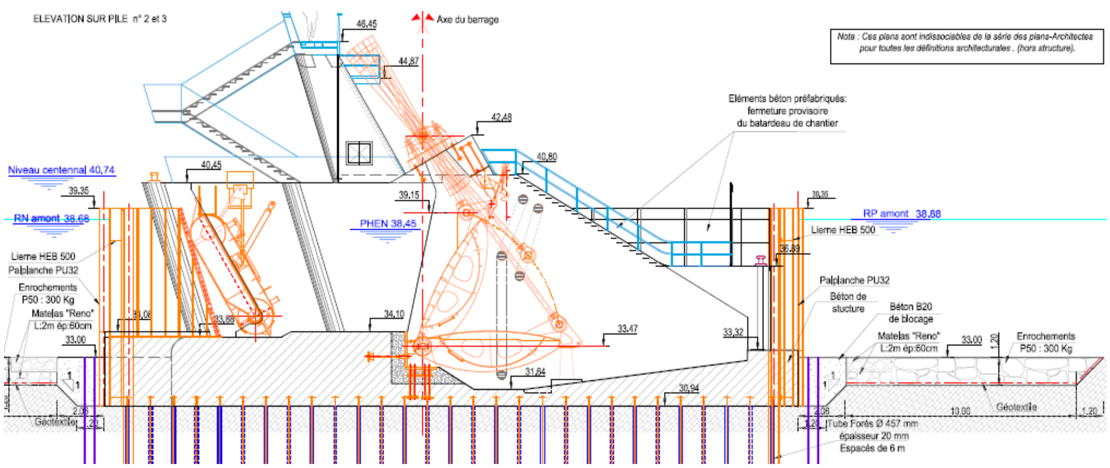


figure 5 - Vives Eaux

2. COFFERDAM AND FOUNDATIONS

2.1 General

The 3 works have been made in complex situations:

- Need to obstruct only 1/3 of the river width to allow flow, and thus to build in 3 years out of the high waters period.
- Need to remove the cofferdam quickly if the discharge is beyond a given limit (for example 10y discharge for Chatou)
- Cracked bedrock close to surface, difficult to watertight .

The bedrock near surface prevented from using the more classical technique for weirs: sheetpiles cofferdam with a underwater concrete plug, to allow the cofferdam stability and watertightness.

The techniques had to be adapted during the final studies or during the work itself, which demonstrate the importance to have, as soon as possible, dense enough geotechnical data on nature of soil and crack density, permeability and capacity to drive sheetpiles.

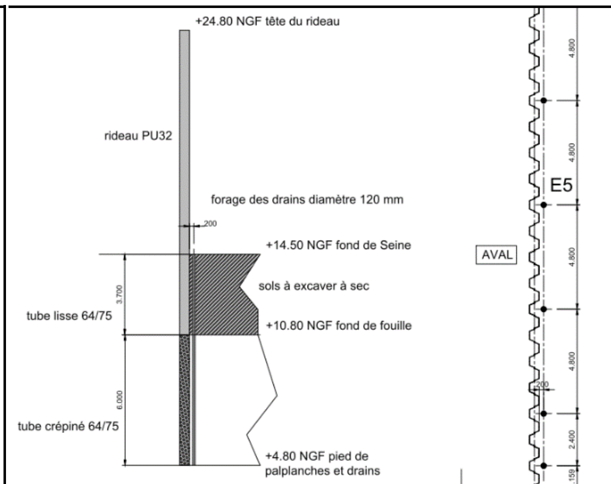
2.2 Chatou cofferdam

The chalk is covered with a sediment layer from 50 cm to 6m, with a cracked and pervious chalk layer, 1 to 2 m thick. As it was possible to drive sheetpiles on this site, the cofferdam was made up of high inertia PU32 sheetpiles, anchored 7 m in the good chalk, reinforced by a brace systems made of walers and struts. 700 tons of sheetpiles GP PU32 and 400 tons of braces has been implemented to realize retaining structures. The cofferdam excavation bottom was 13 m under the Seine river water level, and the earth volume reached 3700 m3 not including polluted sediments dredging.

In the geotechnical conditions ot Chatou weir, it was audaciously considered, since the design stage, that the cofferdam dimensioning could mainly rely on the intrinsic characteristics of good chalk reached at the excavation bottom. In order to accommodate hydraulic constraints imposing unleash clogging between December 1st to March 31th, Tractebel, the project manager, proposed a cofferdam without prior submerged concrete plug, to guarantee a short execution time with respect to the working volume to realize in 8 months.

This proposal has been maintained during working stage, based on the results of geotechnical investigations showing good and homogeneous characteristics. The stability of cofferdam structure is brought by the bracing system completing the bottom support point, only given by foundation soil, as indicated in the following picture.

Excavation bottom earthworking



: Piezometer in the periphery of enclosure E5

figure 6 - Vives Eaux excavation bottom Figure: piezometer I the periphery of cofferdam

In order to manage geotechnical and hydraulic remaining risks, piezometers have been implemented around the cofferdam in the recess of sheetpiles wall as indicated in the figure above. These technical arrangements aimed to detect possible lateral leaks in the chalk bedrock potentially created by sheetpiles driving. These leaks can be caused by the sheetpiles detachment and, in the same time, a separation of the sheetpiles interlocks. This defect can't be detected solely by the interpretation of driving curves, which are not sufficient to assess residual risks.

The cofferdam has been realized in the following order: left bank span (including an abutment and a pier), central span (including one pier), right bank span (including the other abutment). Water pressure on the wall implemented in the flow direction was transmitted to the ground for the left and right banks. For the central span these efforts were transmitted to the pier, already made during the first year, which created difficulties for the support point of the upper waler as it was impossible to install anchoring devices for architecture reasons.

At each work stage, the piezometer measures have been compared to the theoretical profiles in order to detect, as far as possible, increases of water pressure or leaks which could threaten the local stability of an area of the excavation bottom and then the sill integrity. Such phenomenon happened three times during earthwork at the excavation bottom at the contact of banks (and earth retaining elements) which can have local earth peculiarities that are unpredictable before and during works. As soon as a breach happened at an interlock, the required repair consisted in restoring the water level and in setting, with the help of divers, a submerged concrete reinforcement confined behind a steel plate fixed to sheetpiles. If appropriate, this action had to be completed by injections out of the cofferdam enclosure.

On a part of the fish pass cofferdam, indurated chalk was encountered. As it was impossible to drive sheetpiles, an excavation was made under water and submerged concrete was set which slowed the work in progress.

2.3 Le Coudray Cofferdam

The tests carried out during the works showed the great difficulty to drive sheetpiles even with pre-drilling. That's why, after a proposal of the contractor, the cofferdam was made as follows:

- First temporary cofferdam set on the riverbed with head and bottom braces
- Tubular piles bored in the rock and connected to the sheetpiles to insure stability
- Watertighted concrete cordon
- First attempt to dewater the cofferdam.
  It wasn't possible to watertight because dewatering made water come under sheetpiles, and also soil come out of vents, with some risks of piping. A new cofferdam concept was studied and consisted of a cut-off wall with cement injections instead of sheetpiles impossible to drive.
- Injections in the fractured rock in order to watertight it.
  Every 1.2 m on 2 staggered lines, at 50 cm and 1 m around the cofferdam. The depth was 3 m, excepted for 1/6 for which it was 6 m. The goals of these injections were to improve concrete rock contact and to fill and clog cracks.
- First cofferdam cut 1,5 m above ground before floods (tubular tubes let in place)
- 2nd cofferdam made of sheetpiles connected to previous ones

The injected volume has been 122 m^3. 20 m^3 has been injected under the concrete sill to fill the holes created at the first pumping attempt. The injections limited the water inflow at an acceptable value of approximately 550 m3/h.

This new and innovative technique studied and decided during work, led to a 2 years delay and an 40 % additional cost. That's why it was considered at the design studies stage for the Vives Eaux weir located in a similar geotechnical situation.

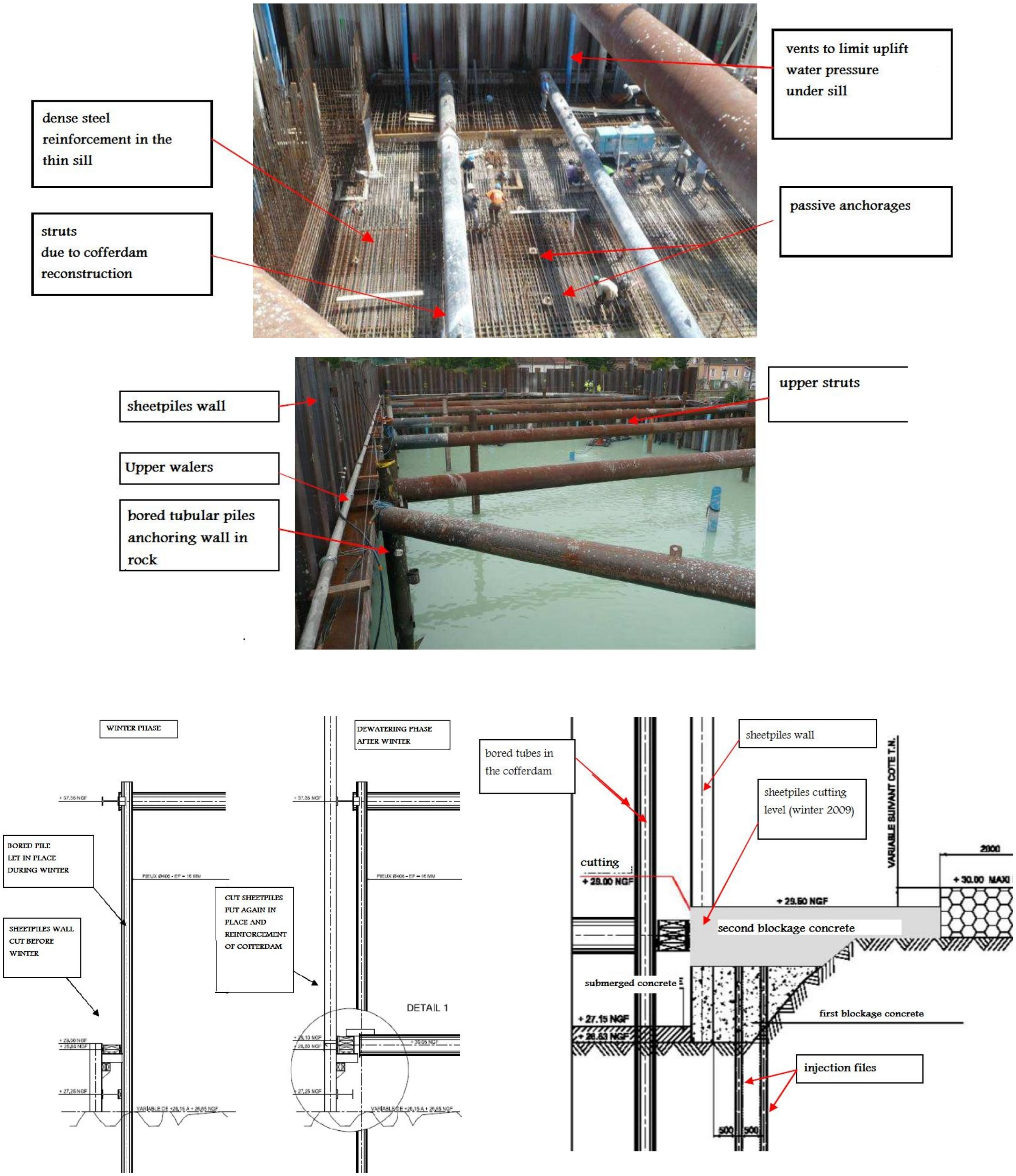


Figure 7 Le Coudray Cofferdam

2.4 Vives Eaux Cofferdam

As it wasn't possible to drive sheetpiles, the previous and difficult experience of Le Coudray has been used. The cofferdam is made of sheetpiles only set on the riverbed, and held by two lines of walers fixed to bored piles every 6 m. Strut at the upper level reinforced the sheetpiles wall. There was no submerged concrete plug.

Technical characteristics of various cofferdam elements can be described as follows:

- piles: diameter 457 mm, thickness 20 mm, spacing: 6 m
- 2 lines of walers HEB 500
- struts; diameter 610 mm, thickness 16 mm, spacing: 7 m et the level of the upper walers line.

Cofferdam has been realized as follows:

- earthwork, realization of sheetpiles set place
- implementation of a gabion cordon around the excavations
- implementation of bored piles
- implementation of walers lines
- setting of sheetpiles
- casting of concrete at the sheetpiles foundation (using gabions as a formwork)
- injections to form a peripheral wall
- realisation of anchorages
- implementation of struts
- dewatering of the cofferdam

The injections ensure the watertightness and limit the internal erosion and undermining risk. They were made through the concrete foundation at approximately 60 cm from sheetpiles wall, in 3 phases with a 3.6 m spacing (phase 1), then 1.2 m spacing (phase2), and finally in staggered row with phases 1 and 2.

During the work a flood happened and the contractor wasn't able to remove the cofferdam in time. So there was an over water height upstream but without significant consequences.

2.5 Sill design

Concerning the Chatou weir, the sill thickness varies from 2.1 to 4.8 m. It has been anchored in chalk by micropiles 10.3 m deep with spacing of 3.25 x 3.25 m in order to resist to hydrostatic uplift pressure. In 2009 the Eurocode became mandatory. It led to increase significantly the steel reinforcement of concrete sill, to avoid concrete cracking due to tensile stresses

For the Weir of Le Coudray, It wasn't the best solution to make a thick submerged concrete plug replacing rock which is very difficult to remove. That's why the concrete plug has been rather thin and strongly anchored by 82 passive micropiles (HA50), 10 m deep, with a grid spacing from 2.5 x 2.5 to 4x4 depending on the location.

3. DESIGN OF FLAP GATES AND OPERATORS

3.1 General

For the 3 weirs, each gate has 2 hydraulic cylinders. However, each cylinder is capable to support alone the whole effort in case of failure of the other one, which is the higher load case. The gates are made of steel S355.

General characteristics

	Chatou	Le Coudray	Vives Eaux
Span width (L)	32.5 m	34.2 m	30.2 m
Water height on sill (H)	7.76 m	6 m	4.8 m
Water fall	3.25 m	3.21 m	2.71 m
Flap gate type	torque tube	fish belly	fish belly
Gate weight : P → P/ L.H → P/ L.H² →	167 tons 662 kg/m² 85 kg/m³	117 tons 570 kg/m² 95 kg/m³	63 tons 435 kg/m² 90 kg/m³
Gate thickness	2.75 m	2 m	1.62 m
Number of hinges	12	12	10
Max deflection	77 mm	34 mm	22 mm
Number of bolts	570 class 10.9	900 class 8.8	534 class 10.9
Max effort on a actuator - normal service - with only 1 operating	380 tons 700 tons	230 tons 400 tons	tons 300 tons
Oil pressure	218 bars	250 bars	250 bars
cylinder rod stroke	9.25 m	7.3 m	6.2 m
Diameter of hydraulic cylinder	670 mm tige:220 mm	480 mm	480 mm

The weight per square meter of closure (considered vertically – P/LH), logically increases with water height. However, P/LH² (linear weight divided by H²) seems to be more stable around 90 kg/m³, which can indicate that the optimisation levels are similar but not equal, especially in the comparison between fish belly and torque tube.

For 3 weirs, the gates have been fabricated in several parts, lifted inside the cofferdam by a crane, precisely implemented and then assembled by bolts.

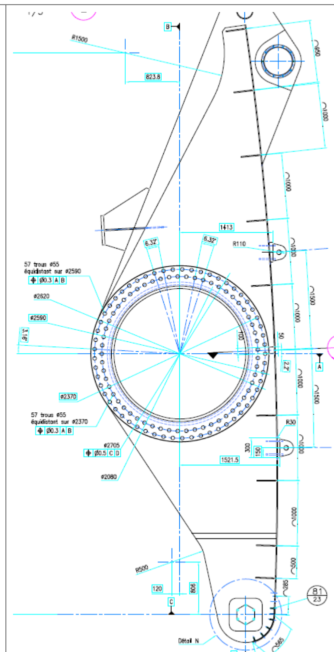
The procedure described below for Le Coudray is representative of the 2 others.

3.2 Chatou Weir

The gates have been fabricated in 6 identical sections which were 5.5 m wide. They are bound only by the torque tube, but the 6 flap parts of the gate are independent structures only linked by a joint. The 6 torque tubes sections are connected by circular flanges welded on the tubes and assembled together by pre tensioned bolts. Unlike studies, the torque tube gate has been proposed by contractor, who considered that it was too complex to realize 9 m long joint surfaces, with the high precision necessary to a correct transmission of efforts. This tube was watertight reducing the weight and the effort on the hydraulic cylinder. Theoretically, the shortcoming could be a slightly heavier and thicker flap gate (2.75 m instead of 2.5 expected by first studies for fish belly gate). The potential consequence should be a higher recess in the stilling basin, which could lead to lower the whole concrete structure by 25 cm with an effect on cost. In this case, it wasn't a significant design criterion and the concrete structure wasn't modified.

The hydraulic cylinders are mounted on cardan joint supports turning on self-lubricating bronze rings, and allowing rotations in 2 directions to compensate the deformations due to gate bending. In normal service, the gate inclination varies between 3 and 66° with respect to horizontal. During maintenance stops they are supported by special locks, relieving the cylinders.

Figure 8 - Chatou gate sector lifted - Cardan joint



Chatou gate plan

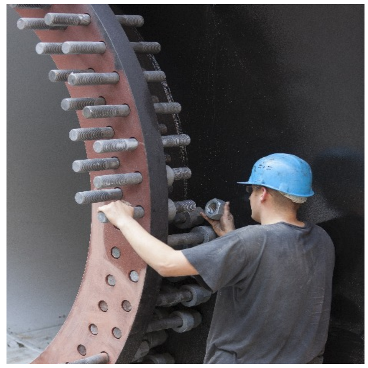
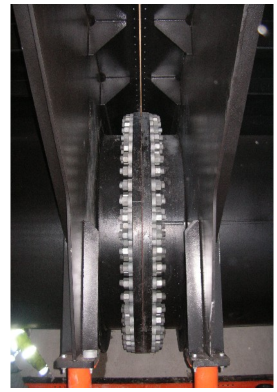
  

Figure 9 - Chatou gate : gate in the cofferdam - bolting - bound tubes

figure 10 - General view (fish eye)

3.3 Le Coudray weir

It has an optimized fish belly shape. To handle it more easily, the flap gate has been transported in 4 sections. They had approximately the same weights and dimensions, but are not symmetrical. As a matter of fact, it's better to avoid locating the joint surface in the middle of flap gate, on the higher stress plane.

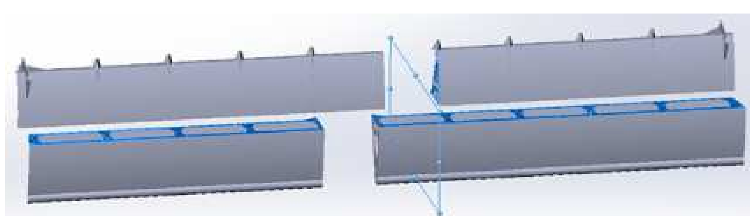


Figure 11 - Le Coudray weir: 4 gate sections

The mounting has been made with following steps:

- Adjustment and sealing of hinges.
  The tolerance was only 1 mm. The hinges had pre-stressed anchorage rods intended to be sealed in concrete with great precision. A perfect alignment was necessary for hinge axes: use of topographic control and piano strings.

- Transport and set up the first section.
  The gates are lifted by the crane on a system of rails in the cofferdam that allows to move them to their final position.
- Coupling: the axes of rotation are put in place
- Set up other sections and bolting.
  The parts are bound by HR bolts (high strength) with controlled tightening using a hydraulic wrench, completed by a sealing bead on each laying plane.
- Tightening
- Dry tests then tests in water


Figure 12 Le Coudray Weir: gate lifted to the cofferdam

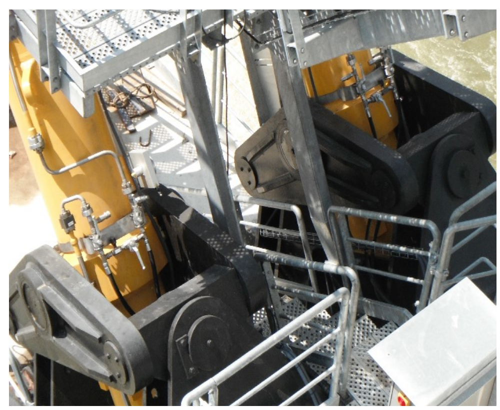



Figure 13 Hydraulic cylinders - vents downstrean of the gate - cardans joints

3.4 Vives Eaux Weir

The principle is the same but in the meantime, regulations have evolved, due to the inclusion of Eurocodes. In addition, the weight per m² was reduced by 1/4 between the two weirs thanks to the optimization of the design. However, if we consider that the efforts are generally rather proportional to the square of the height, we find comparable ratios because the height is lower by 20%. The optimization concerns the manufacturing time by reducing the thickness of weld seams and the simplification of parts, as well as on the lightening of certain parts.

Figure 14 : Vives Eaux - gate lifted

4. HYDRAULIC DESIGN OF THE SILL AND STILLING BASIN

4.1 Le Coudray weir

The sill is designed to accommodate the horizontally lowered flap gate. It must also allow the location of the hydraulic jump on the concrete, as long as it is not drowned by downstream level, in order to limit downstream erosion. In order to optimize this design, a 1/12 scale model has been developed for Le Coudray weir. It represents the gate, the energy dissipation basin and the rip-rap protection downstream. The dimensions are 8 m in length and 1.4 m in width, and represent 96 m on 16.8 m in reality, ie. half a gate, which is sufficient because the phenomena are bi-dimensional. The measurements made by sensors are: the flowrate introduced into the model, the water levels upstream and downstream, the pressures under the gate (frequency of 100 Hz), and the forces on the gate.

The model thus made it possible to determine:

- the flowrate according to the position of the gate (relation head-discharge)
- the hydrodynamic efforts.
- the length of the dissipation basin and the length and characteristics of the rip-rap protection.
- the location of hydraulic phenomena: jet plunge and hydraulic jump
- The aeration of the nappe and nappe dividers on the gate (anti-vibration).

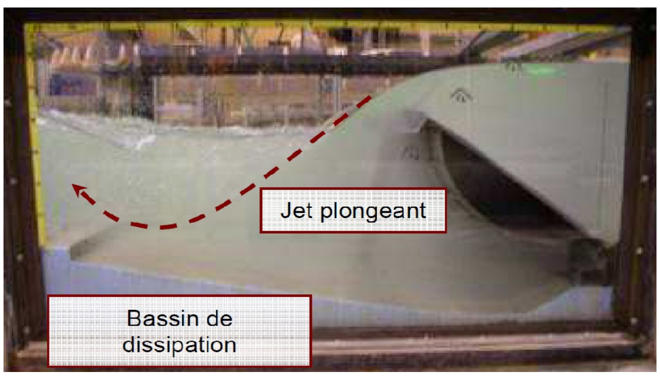


Figure 15 : plunging jet

figure 16 - rip rap

The tests were carried out for 5 possible gate positions (8, 35, 43, 54, 69 °) and 6 possible discharges (representing from 60 to 570 m3 / s on the entire weir). The model has made it possible to visualize the plunging jet, and to check the position of the hydraulic jump, generally in the basin, and sometimes, at the limit of the rip-rap, as well as the stability of the armour stones. Therefore the initial design calculated by classical formulas has not been modified. The maximum hydrodynamic forces on the gate have been evaluated at 200 tons per cylinder by integrating the rapid fluctuations.

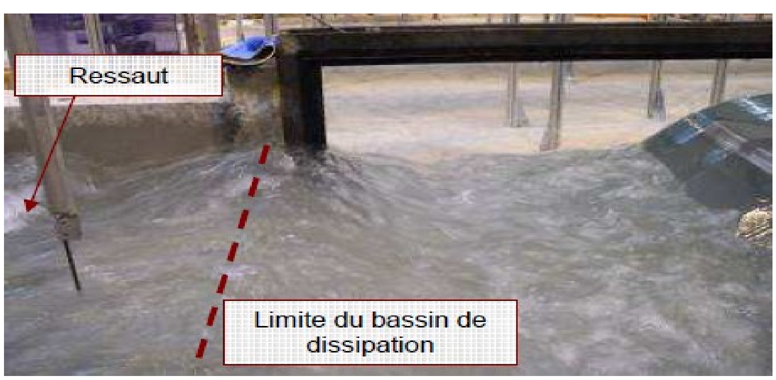


Figure 17 Hydraulic jump after the limit of basin

For an inclination of the gate greater than 35 ° the current dividers installed on the top of the gate are no longer effective. There is then a downstream depression, which causes a vibration of the order of 1.35 Hz. The aeration makes it possible to suppress the vibrations of the gate by resonance. It is made by pipes installed in the wall structure, an connecting the downstream side of the gate to the atmospheric pressure. Three vents have been positioned to provide this function for a maximum of positions. The geometric constraint on these vents is that the exit point is above the downstream level and below the gate.

Dividers have also been optimized by varying their position, shape and number.

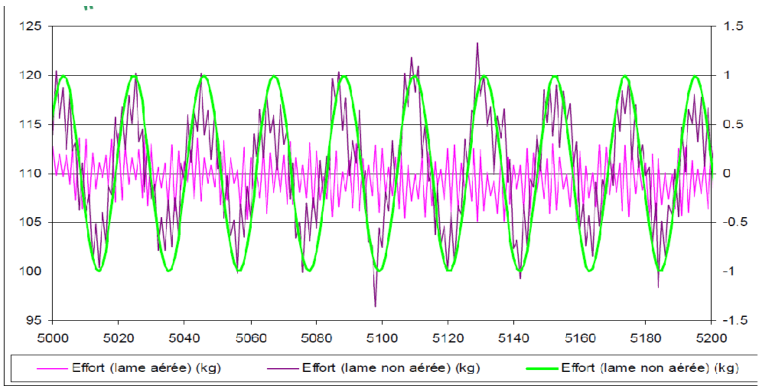


Figure 18 Results: vibration without aeration (green line) and with aeration (red line)

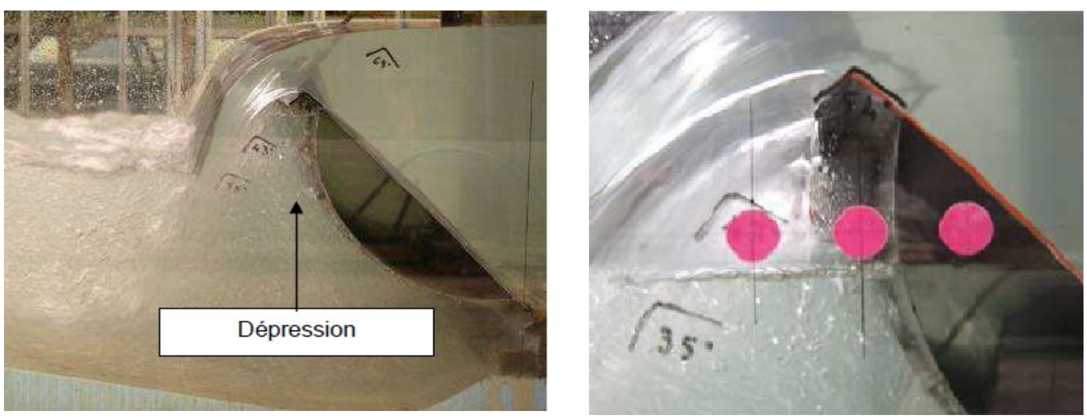


figure 19 View of depression location and position of vents

4.2 Chatou weir

For Chatou, the energy dissipation basin is short, barely longer than necessary to house the lowered valve, which does not allow the top spill to always be well located in the basin. However, the downstream height is important, which favours the dissipation of energy and the ground resistance to scour (chalk).

5. UPSTREAM MAINTENANCE BULKHEAD

The maintenance bulkheads are floating stoplogs, which makes it possible to avoid heavy handling equipment. They are put in final vertical position by filling of the ballasts

Chatou weir Bulkhead

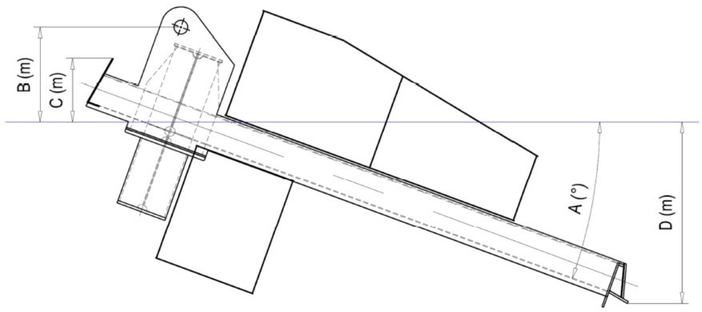


figure 20 - Chatou bulkhead plan with ballasts


figure 21 - Chatou Bulkhead arriving by buoyancy and in final position (first use)

Le Coudray weir

The Le-Coudray bulkhead consists of a stiffened metal decking which is supported on two cylindrical and compartmental longitudinal caissons 1.5 m in diameter. The compartments are equipped with valves and piping for filling / emptying.

For its installation, the bulkhead will be brought by buoyancy. When the roller located on the bulkhead come in contact with the pier equipped with rail guide, the cylinder rods come out so as to allow their attachment to the piers clamps.

In 2018 it is fabricated but not yet in operation. The downstream maintenance bulkhead is simply made up of aluminium beams stacked between vertical H shaped profiles.

For Vives Eaux, old equipment which is also used on 4 other works of the Seine upstream has to be refurbished. For the other 2 the equipment is new.

Figure 23 -Le Coudray bulkhead moored

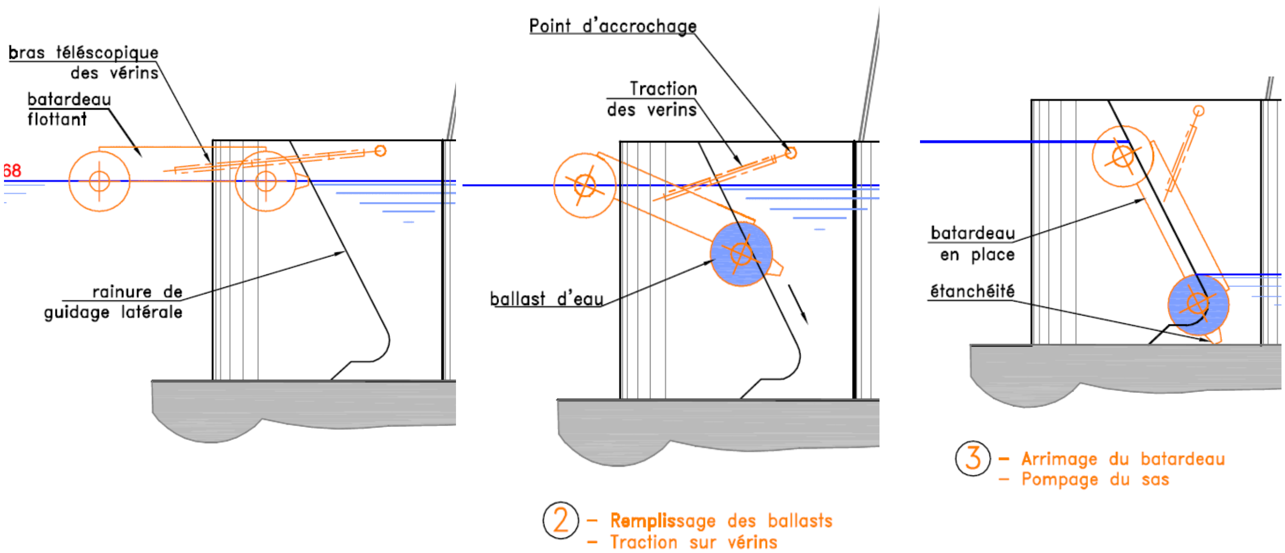


figure 24 - Le Coudray : 3 phases to put the bulkhead in final place

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