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Scale physical model and prototype comparison for a large dam bottom outlet

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ABSTRACT

Scale physical modeling is widely used for large hydraulic structures design. It is recognized as a reliable method to characterize detailed flow conditions at prototype scale. However, similar to numerical models, scale physical models are simplifications of real size flow conditions. That's why, when possible, comparison of scale model data to prototype data has to be done and shared among the scientific and practitioners' community. In this paper, data gained from a large dam bottom outlet operation are compared at prototype and physical model scale (1:35). The structure includes a bottom step aerator, specific downstream channel sidewalls and a complex flip bucket to control the jet impact location in the narrow downstream valley. Prototype tests cover a large range of upstream head with varied gate openings. The comparison shows that, while main flow features have been properly predicted by the scale model, significant differences exist. For instance, flow aeration is much more important on the prototype than on the scale model. Transients have also been properly capture during the experimental tests.

Keywords: *Prototype, Scale physical modeling, Bottom outlet, Scale effects, Air water flows, Scour*

1. INTRODUCTION

Physical models have been used for decades in hydraulic engineering, for both projects design and research. Hydraulic performance data derived from laboratory-scale physical models have been and are still the foundation for most large hydraulic structures design. Indeed, scale models offer as main advantage the ability to reproduce the whole complexity of prototype flows if suitable scale factors and similarity laws are applied (Sutherland & Barfuss, 2011; Heller, 2011). In addition, they act as powerful communication tools in the promotion of projects and engineering solutions (Ettema, 2000), probably because they are "real".

However, scale physical models are only "models", i.e. simplified representations, of the prototype, i.e. the real structure. Full model-prototype similitude is only achieved when kinematic and dynamic similitudes are verified (Kobus, 1980; Ettema, 2000; Heller, 2011; Novak et al., 2010). To do so, fluid properties such as density, viscosity and surface tension, but also gravity acceleration, should be scaled. This means that it is never possible to achieve a full similitude when operating a scale model with water on Earth. For free surface flow, gravity and inertia represent usually the dominant forces. Conservation of their relative influence on a geometrically scaled physical model is done through application of the Froude similitude. Consequently, other fluid dynamic forces such as viscous forces and surface tension are not properly scaled. This leads to so called scale effects, i.e. flow behavior observations on the scale model that do not occur on the prototype (Erpicum et al., 2016; Teng and Yang, 2018).

To overcome this problem, scale models operation intended for prototype application should be limited to flow conditions where not properly scaled processes are negligible. This usually means that small geometric scale factors have to be used (Heller, 2011; Chanson, 2009). In practice, the size of the prototypes coupled to the costs, both in time and money, of large physical models building and operation, prevent from using the required scale factor. Even with small scale factor, for instance 5 or 10, scale effects may exist, for instance regarding aeration effects as full similitude can only be reached at 1 to 1 scale (Pfister and Chanson, 2012; Guyot et al., 2016).

Numerical modeling faces similar problems. Indeed, either the mathematical models solved by numerical software are not able to reproduce the whole of the physical processes underlying the flow conditions, or the size of the prototype prevents from applying a mesh size fine enough to capture all the relevant flow properties.

Finally, the most important difficulty that the hydraulic engineering community has to face is probably the fact that prototypes behavior is poorly documented. Large hydraulic structures are designed considering (extremely) rare events that, consequently, may never be observed. When such a rare event occurs, the structures facing it are generally not equipped for data collection.

That’s why we believe that, when available, any data from prototype operation should be made available to the hydraulic scientific and practitioners’ community. In addition, when possible, comparison of these prototype data to corresponding scale model data should be performed and shared.

In this paper, data gained from a large dam bottom outlet operation are compared at prototype and physical model scales. The structure, presented in section 2, includes a bottom step aerator, specific downstream channel sidewalls and a complex flip bucket to control the jet impact location in the narrow downstream valley, designed using a physical scale model. Performance assessment tests performed just after prototype commissioning are presented in section 3 and compared, when possible, to corresponding data from the scale model.

2. NEW BOTTOM OUTLET AT SARRANS DAM

2.1. Context

The 105 m high Sarrans gravity dam (Figure 1) is located in France, in the Aveyron Department. It has been built from 1930 to 1935 to control Truyere and Lot Rivers discharge in order to produce electricity at several hydropower plants downstream.

In 2011, Electricité de France, the dam and power plants operator, started a project aiming at creating a new bottom outlet at the dam site in order to ease reservoir emptying operations and to complement the discharge capacity of the two old gallery spillways in the left bank of the valley in case of extreme flood events. This new bottom outlet was commissioned in 2015.

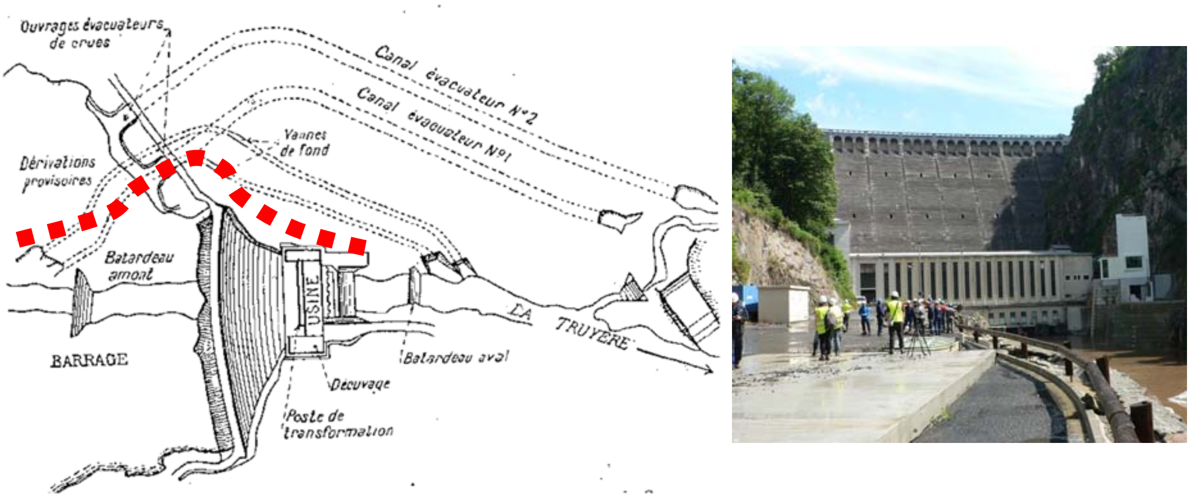


Figure 1: Sarrans dam general arrangement with location of the project (left) and downstream view of the dam with the powerplant at the toe and the new bottom outlet on the right (right)

2.2. Prototype characteristics

The new bottom outlet uses part of the old bottom outlet gallery on the left bank of the reservoir, connected to a new water intake upstream and to a new gallery section downstream, whose extremity is closed by two successive lift gates. To accommodate elevation differences between water intake and old bottom outlet gallery on the one side and new gallery on the other side, a new S shape gallery has been built to connect both parts (Figure 2 - left). At normal reservoir level, the static head acting on the gates is close to 80 m.

At the gates, the gallery is rectangular with a width of 2.8 m and a height of 3.5 m. Downstream, a free surface flow channel and complex flip bucket have been designed using a physical scale model (see section 2.3) to divert the flow in the narrow Truyère river bed at the dam toe (Figure 2).

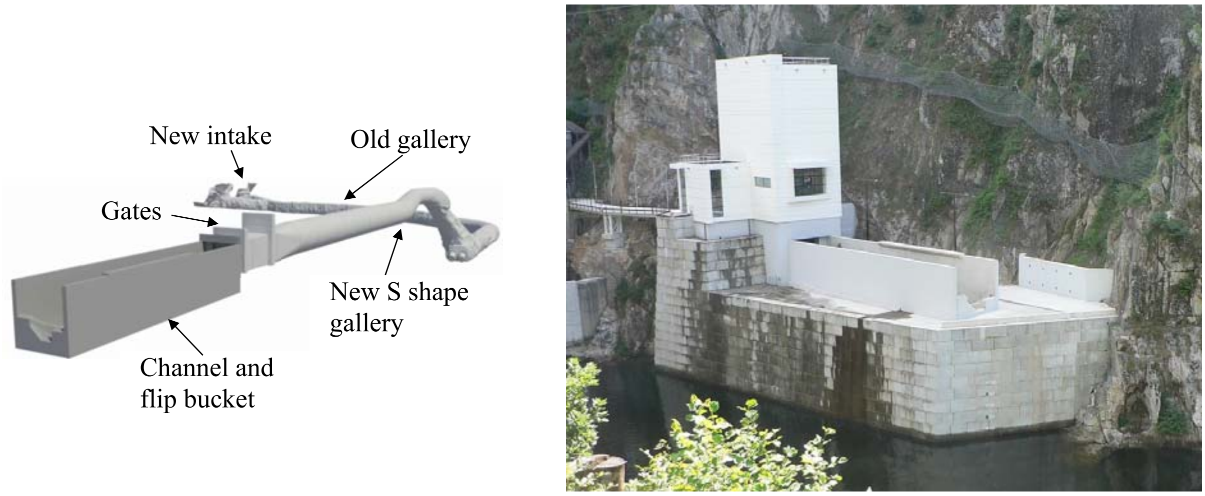


Figure 2: 3D view of the new bottom outlet circuit (left) and downstream extremity of the system (right)

2.3. Hydraulic scale model

At an early stage of the new bottom outlet design, Electricité de France commissioned the Engineering Hydraulics Laboratory of Liege University to build and operate a hydraulic scale model of the downstream extremity of the system in order to set up and optimize its design. The model (Figure 3) represented the downstream end of the new S shape gallery (inner diameter of 4.5 m, slope of 1%), the circular to rectangular section transition and then the 2 gates on the RCC platform designed by Electricité de France on the left bank of the Truyère river at the dam toe. Downstream, a 230 m long Truyère river valley reach, starting at the dam power plant toe, has been modelled.

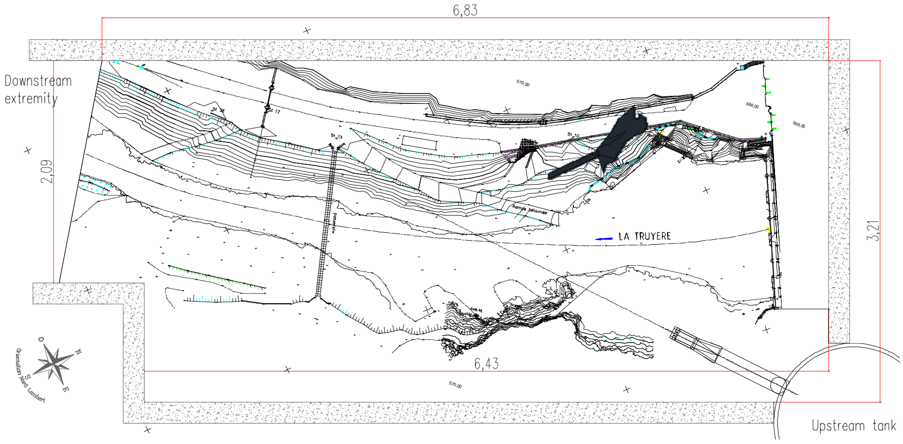


Figure 3: Plan view of the 1:35 scale model. Dimensions in m.

The model has been designed to operate with Froude similitude. Given the limited time available to perform the scale model studies and the tight timing for the new bottom outlet project, the geometric scale factor has been defined considering the space available in the laboratory to start immediately the model construction. This scale factor was 1:35. This means that the design discharge of 225 m³/s was 0.031 m³/s at model scale and that the 23 m/s flow velocity at the gates on the prototype was 3.9 m/s on the scale model. Reynolds number is around 6×10^7 on the prototype and was 3×10^5 on the scale model. Corresponding values are 2×10^7 and 2×10^4 for Weber number.

A tank upstream of the gallery section and a butterfly valve connected to the tank outlet enabled controlling the discharge and the head applied upstream of the model. The tank was supplied with water using the regulated pumps of the laboratory. Downstream of the model, a perforated tilting plate, placed perpendicular to the valley axis, was used to adjust the water level in accordance with the rating curve provided by Electricité de France. The concrete structures have been built using PVC, synthetic resin and aluminum while the topography has been modeled with cement mortar (fixed bed) or 8-16 mm rounded gravel (mobile bed). The model has been operated with both a mobile and a fixed bed for the river reach (Figure 4).

Discharge was measured using an electromagnetic flowmeter (accuracy +/- 0.001 m³/s). Point gauge (accuracy of 0.001 m) was used to measure downstream water levels. Flow velocity measurements in the Truyère river has been done using a micro propeller. Static pressure tubes were placed on the free surface channel side walls and the flip bucket to measure pressure (reading accuracy of 1 mm). In case of fixed bed, a regular grid 0.2 x 0.2 m has been used to localize jet impact area.

Figure 4: View of the 1:35 scale model with mobile (left) and fixed (right) bed

The geometry of the downstream channel (section, length, slope, flip bucket - Figure 5) has been defined during the tests in order to control the jet trajectory and the impact location in the downstream valley. A sharp transition from the gate section to the channel section was ensured, laterally and vertically, to enable aeration of the flow.

Figure 5: Channel and flip bucket final geometry on the prototype (left) and the scale model (right)

24 configurations have been tested for the channel and the flip bucket geometry. The final design is made of a 4.6 m wide and 26 m long channel with a 3% slope, inclined on the left of the gallery axis with a 3.9° angle. The vertical side walls height increases from 4.2 m upstream to 5 m downstream. The channel bottom is set 0.7 m below the elevation of the gallery. A complex flip bucket has been designed at the downstream extremity of the channel. This geometry has been found satisfactory to deviate the flow from the gallery in the axis of the downstream valley, to optimize the jet impact area and location as well as to control the downstream flow conditions (avoid recirculations) in a large range of discharge. A cap on the top of the channel left bank prevents overtopping for intermediate discharges.

3. PROTOTYPE OPERATION AND COMPARISON WITH SCALE MODEL RESULTS

3.1. Discharge capacity and tests conditions

The complex geometry of the gallery (S shape section) and its roughness (partly unlined rock) induced significant uncertainties in the evaluation of the bottom outlet discharge capacity. However, contrary to what happens with surface spillways, bottom outlet works do not need a flood to operate at discharges close to the design discharge. Consequently, as far as large discharge events can be accommodated in the downstream valley, it is possible to realize validation tests for this type of hydraulic structures. Such tests have been done by Electricité de France in 2014 and 2015, during reservoir filling, in order to validate the hydraulic design of the new bottom outlet and to increase the accuracy of the head/discharge relation (Blancher et al., 2017).

Tests have been performed at 4 reservoir levels starting below the minimum operating reservoir level to the normal reservoir level. In each case, discharge at full gate openings has been estimated by two different techniques: velocity field measurement and integration using an Acoustic Doppler Current Profiler (ADCP) in the downstream river reach (2 estimations at different locations) and time evolution of the downstream Barthe dam reservoir volume. Test duration was usually 10-15 min, i.e. the time needed to open fully the gate and then to close it. The last test at full capacity lasted 2 hours to enable accurate discharge estimation.

Table 1. Prototype discharge measurement and final estimation with uncertainty (95% interval)

			Test 1	Test 2	Test 3
			m^3/s		
Measures	ADCP	Section 1	62.8 +/- 6	132.0 +/- 13	251.0 +/- 25
		Section 2	59.0 +/- 12	137.0 +/- 27	259.0 +/- 39
	Barthe dam reservoir		64.5 +/- 2	146.0 +/- 6	286.0 +/- 12
Final discharge estimation			62.1 +/- 7	138.0 +/- 15	265.0 +/- 12

Discharges estimations showed that the capacity of the bottom outlet at normal reservoir level is higher than expected. Design discharge, considered for the scale model study, was 225 m^3/s, while measured discharge on the prototype was found to be 265 m^3/s (+/- 5% uncertainty). This is a first take at home message from this project. Uncertainties may also affect design parameters. Fortunately, scale model tests also considered higher discharges than the design one. In particular, a design of 260 m^3/s was used to verify the good hydraulic behavior of the system in “extreme” conditions. In addition to discharge values, the tests on the prototype provided visual information on the flow features over a large range of discharges and gates openings. These observations are used in the sequel for the seek of comparison with the scale model results.

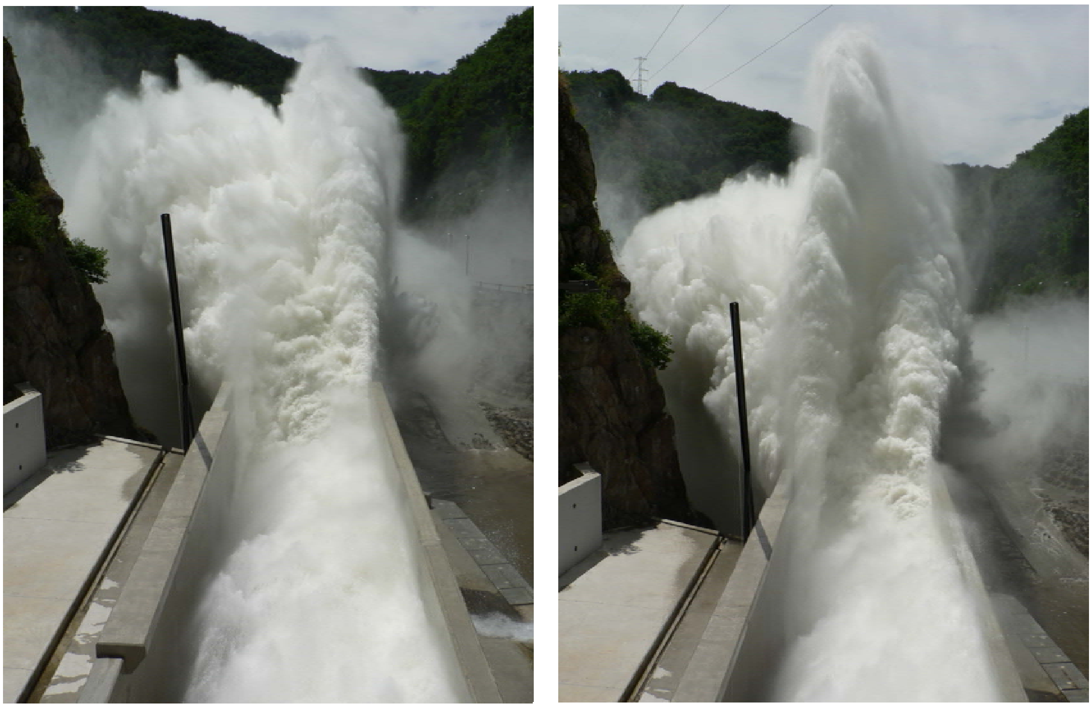
3.2. Flows in the channel and on the ski jump

Figure 6 shows the evolution of flow conditions in the channel and on the flip bucket with the gate opening at design head. At small gate opening, spray occurs immediately downstream of the gate, hiding most of the flow patterns in the downstream channel. Flow appears to be disturbed, with transients and local spillage over the sidewalls. Above 10 to 15% of gate opening, flow becomes steadier and a jet detaches from the flip bucket. Lateral spillages decrease progressively. At full gate opening, the channel contains the flow and deviates it properly to the left as predicted by the scale model tests. The flip bucket influences strongly the flow features, as noticed on the scale model. A jet going up very high is observed on the left side as it is pushed up by the main discharge coming from the right because of the channel inclination and the flip bucket dissymmetry.

Except flow aeration that is much more important on the prototype than on the scale model, the main flow features at constant discharges are similar on the scale model and the prototype (see figure 7 for instance). It is not the case during transient phases. In particular, the cap on the top of the channel left sidewall, designed to prevent spillage during intermediate openings, seems to be useless on the prototype, while a similar cap on the right side wall would have been useful (Figure 6).

t = 1min (≈10% opening)

t = 2min (≈20% opening)



t = 4min (≈40% opening)

t = 10min – Full opening – 265 m³/s

Figure 6: Flow in the channel at gate opening – Upstream reservoir at normal operating level

3.3. Jet and downstream flow conditions

Regarding the jet, the main difference between the scale model and the prototypes is aeration, as already mentioned. Huge sprays develop around the main jet on the prototype, preventing to clearly assessing its shape and trajectory. Main features observed on the scale model are however visible on the prototype (Figure 7). The jet is made of two main components: a strong core with a lower trajectory and a deviated jet above the main one, containing less discharge. As a result, the flow from the gallery is properly deviated to the left, along the river axis, with a shape at impact elongated in the direction of the valley.

Figure 7: Jet at design discharge – Scale model (260 m^3/s - left) versus prototype (265 m^3/s - right)

Consistently with scale model observations, no back currents are observed along the right bank of the river. This confirms the adequate design and operation of the channel and the flip bucket. A strong decrease of the river water level is observed upstream of the jet impact (hydro ejector effect). Its amplitude for a discharge of 265 m³/s is around 4 m on the prototype. It was 3.85 m on the scale model for a 260 m³/s discharge. Jet impact distance, carefully measured on the scale model for various gate openings and discharges, were found to be consistent with prototype estimations (Figure 8).

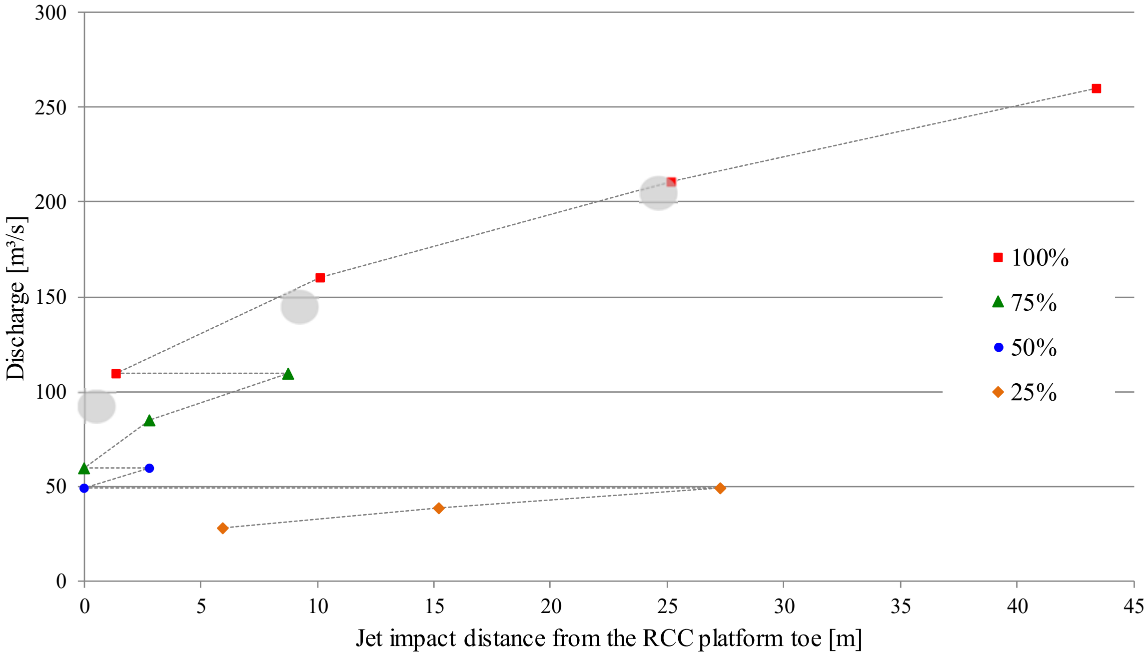


Figure 8: Evolution of jet impact location with the discharge and the gate opening. Scale model results (plain symbols) compared to prototype estimations at full gate opening (dashed area)

3.4. Scour and erosion

Despite the scale model has been initially built with a mobile bed (Figure 4), most of the tests have been performed with a fixed bed. Indeed, it early appeared during the scale model study that the topography of the downstream rocky valley, where very steep slopes can be observed, cannot be adequately modeled with a mobile material without cohesion. Moreover, as no data were available to characterize the real river bed material and rock foundation, it was impossible to try to model it more reliably. Scale model tests focused then on creating flow conditions prone to avoid scour and erosion at critical locations (right river bank for instance) and to decrease as much as possible flow solicitations at other places.

At the end of the prototype tests, it appears that flow solicitations on the right river bank were limited. In agreement with the scale model observations, they were more important on the left bank, leading to local erosion (Figure 9 – right). It is interesting to notice that severe damages to the flip bucket were observed (Figure 9 – left). They are probably due to rocks entrained by the flow, coming from the reservoir or the walls of the gallery in its unlined section. Such rocks where visible in the jet during the tests. Their impact on the flip bucket when ejected from the flip bucket was also audible. Up to 0.2 m diameter rocks have been found on the channel bed at the end of the tests (Blancher et al., 2017).

Survey performed after the tests showed that a scour pit developed on the river bottom just downstream of the jet impact location, with materials deposits visible downstream (Figure 10 - left). The maximum scour depth was found to be around 4 m, with as main problem the undercut of the right bank protection (Figure 10 - right). Reinforcement works have been done to secure this area (Blancher et al., 2017).

Figure 9: Flip bucket abrasion (left) and left river bank erosion (right) after bottom outlet operation at design discharge (265 m³/s)

Figure 10: Deposits downstream after test at minimum operating level (138 m³/s) (left) and scouring after test at half design head (200 m³/s)

4. CONCLUSIONS

Comparison of 1:35 scale model and prototype flow features observed downstream of a large dam bottom outlet showed that the scale model predicted well the general flow conditions such as flip bucket effects, jet trajectory, jet impact location and downstream flow patterns including water level decrease (hydro ejector effect) induced by the jet impact. However, flow aeration was found to be much more important on the prototype. Transients were also poorly predicted by the scale model.

This paper recalls that, in hydraulic engineering, scale physical models are simplified representation of the reality, i.e. the prototype. Numerical models face a similar problem. Consequently, when available, any data from prototype operation should be made available to the hydraulic scientific and practitioners' community. In addition, when possible, comparison of these prototype data to corresponding scale model data has to be done and shared in order to help to improve our understanding of hydraulic models and the use that can be done of the results they provide to assess the behavior of prototypes.

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