Laboratory research: Bed load guidance into sediment bypass tunnel inlet

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Abstract

Sediment management in reservoirs situated in mountainous regions is a critical operational concern with direct implications in live storage sustainability and therefore in production revenues. The paper presents the main results of a physical model study of a sediment evacuation system foreseen for a large hydropower scheme in Ecuador, carried out at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). The system comprises a sediment bypass tunnel (SBT) and a submerged weir nearby the gated tunnel inlet, conceived mainly to bypass bed load sediments. Four operation modes were identified and documented. The final sediment bypass efficiency is almost 100% for frequent floods under upstream drawdown, reducing to 20% for larger flood events above the capacity limit of the bypass tunnel. The tests resulted in an improved configuration of the system in all operational modes, including reverse flushing. Guidelines for prototype operation were proposed to consider, among others, the sequential combination of high and low reservoir levels and different gate openings, during and after floods events, in order to improve the overall sediment bypass efficiency.

Zusammenfassung

Das Management der Stauseeverlandung im Berggebiet ist von grosser Bedeutung, es hat direkten Einfluss auf das Nutzvolumen, den nachhaltigen Betrieb und somit auf den wirtschaftlichen Ertrag. Es werden die wichtigsten Resultate einer physikalischen Modellstudie aufgezeigt, bei welcher der Eingangsbereich eines Sedimentumleitstollens einer grossen Wasserkraftanlage mit Stausee nachgebildet und dessen Effizienz getestet wurde. Die Versuche wurden am Laboratoire de Constructions Hydrauliques (LCH) der Ecole Polytechnique Fédérale de Lausanne (EPFL) durchgeführt. Vier Betriebsarten können identifiziert und dokumentiert werden. Die am Schluss erhaltene Sediment Bypass Effizienz erreicht beinahe 100% für häufige Hochwasser dank Absenkung im Oberwasser, dieser Wert reduziert sich auf 20% bei Abflüssen im Bereich der Kapazität des Sedimentumleitstollens. Die Versuche führten zu einer optimalen Auslegung der Anlage für allen Betriebsarten, inklusive der Umkehrspülung. Es konnten Richtlinien für den effizienten Prototypbetrieb erarbeitet werden, welche unter anderem den

variablen Seestand und verschiedene Schützenöffnungen während und nach einem Hochwasserereignis berücksichtigen.

1 Introduction

Maintaining the operational live storage of hydroelectric reservoirs in high sediment-yield river catchments is a challenge for operators wishing to guarantee yearly energy production, revenues and debt reimbursement. Failing to convey downstream part of the sediment inflow may lead to progressive aggradation of the reservoir bathymetry, increased sediment loading on dams and increased entrainment of sediment in hydraulic structures such as power intakes and clogged bottom outlets. Equipment wear and damage increase the operational expenditures and the risk of production stoppage and loss of revenues. Therefore, active management of sediment bed load inflows has become common practice in some alpine catchments and power schemes, namely for storage dams with short reservoirs and large annual drawdown ranges, as well as for low-head dams with shallow reservoirs.

Some experiences have been gained in terms of bed load transit from upstream to downstream by carrying out regular flushing operations through the bottom outlets (typically for dams higher than 15 m) and through the spillway gates (for low-head dams). Operations without lowering the reservoir level have local impact, whilst operations with reservoir drawdown may allow for larger sediment outflows. The former is done with small operational impact whereas the later implies stopping production for at least some days. The sediment concentration flowing downstream must respect environmental constraints and regular purging operations must be scheduled with and authorized by the public authorities. However, purging operations are not only cumbersome and costly, but also often not concomitant with natural floods and therefore not reproducing the original river regime. The present legal framework in Switzerland requires the partial reestablishment of bed load transit as part of a policy to maintain riverbed morphology and ecology. Therefore, the present challenge is to develop sediment transit concepts that not only extend the lifetime of reservoirs at minimum cost but also contribute to the reestablishment of the morphological diversity downstream. One solution is the construction of sediment bypass tunnels (Vischer et al. 1997, Morris 1997). However, most developments answer specific project needs as no general design rules or operational guidelines exist yet (Sumi et al. 2004). Optimization of such tunnels should consider conveying bed load downstream during natural floods, reducing the impact of sediment flushing operations on hydropower production and positively contributing to maintaining the live storage.

The work presented in this paper contributes to the achievement of these goals by presenting a case study in Equator for which a new operational concept using a sediment bypass tunnel was developed and then tested, validated and optimized through physical modelling.

2 Background on sediment bypass tunnels

The first BPTs were built in the early 20th century in Japan and Switzerland (Vischer et al. 1997; Sumi et al. 2004), construction rate reducing to an average of about one per decade until the early 2010's. These tunnels are designed for free-flow operation, with design velocities between 7 and 15 m/s, hydraulic sections between 20 and 30 m^2, general slopes from 1 to 4%, design discharges from roughly 40 to 400 m^3/s, most of them being operated less than 30 days per year. A typical layout includes a tainter gate as regulating device at the inlet, leading to a flow accelerating reach followed by the typical cross section reach with the general slope until the outlet and energy dissipating structure.

SBTs are becoming more popular due to increased concern about the sustainability of live storage (and revenues) and of growing public interest to reduce reservoir trap efficiency and guarantee sufficient sediment transfer to downstream river reaches and maritime coastlines. Kondolf et al. (2014) present an overall balance of live storage depletion worldwide due to sediment trapping, which inevitably reduces mankind's ability to supply water & electricity to a growing population. Sediment trapping simultaneously aggravates the deficit of sediment replenishment vital for territorial security and biodiversity downstream. Not surprisingly, a larger number of countries has been adopting policy measures to reinforce monitoring of sediment bed load within river basin management.

Recent research on SBTs focuses on the resistance of the tunnel invert to hydroabrasion (Boes et al. 2014) and well as the SBTs' efficiency combining fieldwork and numerical modeling. Kantoush et al. (2012) measured at prototype scale the flow characteristics and suspended sediment concentration (SSC) in a SBT in Japan during flood seasons, which revealed to be instrumental to calibrate previous numerical model studies. However, other sediment management solutions are being developed in parallel that could be combined with SBTs to increase the overall bypass efficiency (BE), such as venting of suspended sediment (SS) through bottom outlets, turbining SS, flushing with drawdown and so forth. As an example, Jenzer-Althaus (2011) developed an original system that mobilizes fine settled material allowing for its easier flushing. The system is composed of water sprinklers disposed such as to generate cyclonic motion in areas where main flow velocities would be high enough to push the SS downstream (through the SBT or another device). However, no information was found on the damage incurred further downstream at the SBT outlets or of any specific design criteria adopted for the energy dissipation structures with regard to clear-water structures from spillways or river diversion tunnels (which are temporary by definition).

3 Chespí dam and hydroelectric power plant

The Chespí-Palma Real hydro power plant is located in the northwestern part of Ecuador on Guayllabamba River, about 30 km north of the capital, Quito. The project is developed on behalf of HidroEquinoccio in Quito. The plant consists of a double curved arch dam, 68 m height, with a reservoir capacity of 4.4 x 10^6 m^3 and an active storage capacity of 2.3 x 10^6 m^3. The reservoir gathers the water of an approximate 4'500 km^2 large basin. The hydroelectric power plant, located in a cavern downstream of the dam, consists of four Pelton units with 470 MW installed capacity (For more information, see Grimaldi et al. 2015).

Sediment management is a fundamental aspect of this project. The estimated mean annual sediment flux is some 820'000 m^3. If no action is taken, the reservoir would be filled-up within some years. To avoid regular drawdown flushing of the reservoir and subsequently the plant shutdown, a sediment bypass structure is planned upstream of the reservoir. An underwater sill, located immediately downstream of the inlet structure is used as an obstacle in the main river course, preventing excessive sedimentation of the reservoir. Two alternatives sill locations were defined during the design stage; the first one (called hereafter "upstream sill") is situated right next to the inlet structure and the second one (called hereafter "downstream sill") is placed further downstream.

4 Sediment bypass concept

The sediment bypass concept with four main stages, outlined by Lombardi and further developed by the LCH (De Cesare et al. 2012) is explained hereafter (Figure 1):

a) **Normal reservoir and hydropower plant operation;** the SBT remains closed, the mainly clear (with negligible suspended sediment) upstream inflow passes over the sill into the reservoir. Latent bed load is retained upstream. There is no limitation on hydropower exploitation.

b) **Upstream drawdown flushing and transfer**. When the upstream discharge reaches a level that triggers bedload, SBT can be partially opened to transfer bedload (to ensure transport capacity in the SBT); lowering the water level upstream will accelerate bedload flushing, keeping the inlet structure free of deposits.

c) **SBT use under full load.** When the inflow discharge exceeds the SBT capacity, water level rises, the excess discharge flows over the sill into the reservoir and may require spillway operation. Bedload is continuously evacuated through the SBT. Suspended load is split, partially being evacuated through the SBT and the remainder settling close to the dam

d) **Reverse flushing with drawdown.** At the end of a flood event, water flowing back from the reservoir is evacuated through the SBT, keeping the zone between the sill and the inlet structure free of deposits.

During all above-mentioned stages, hydropower operation over the useful capacity of the reservoir can continue.

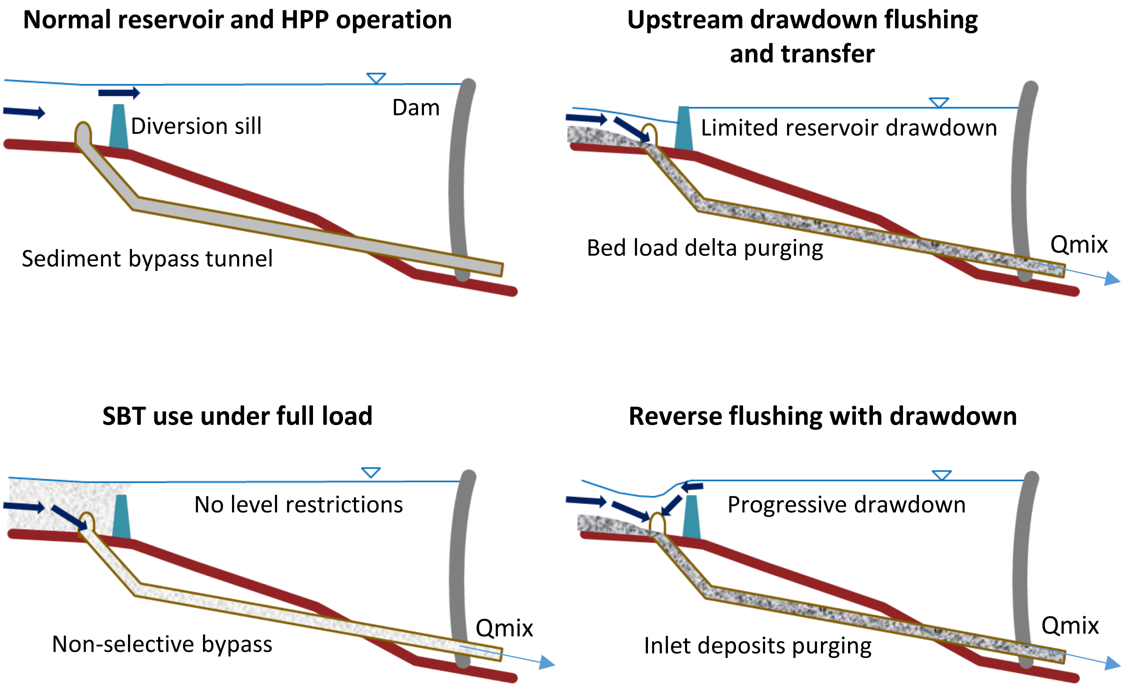

Figure 1: Schematic drawing illustrating the sediment bypass concept for the Chespí-Palma Real reservoir

5 Laboratory model

The objectives of the model tests are to validate and optimize the following aspects:

a) the performance of the sediment bypass in the established configuration;

b) the identification of potential deposit zones in the river; and,

c) the sediment flushing procedure for proper evacuation during floods.

The physical model was built in the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL) (LCH 2011). Based on the dimensions, the discharge as well as the grain sizes, a scale of 1:38 was used. The model was operated according to the Froude similarity. The grain size distribution considered for the study was a $d_{50} = 20$ mm, the maximum reaching some 130 mm. Bedload transport capacity similarity between prototype and physical model has been evaluated using the critical Shields parameter. Taking into account the hydraulic parameters of the considered upstream river reach, a model "bedload" consisting of washed fine sand 0/4 mm was chosen.

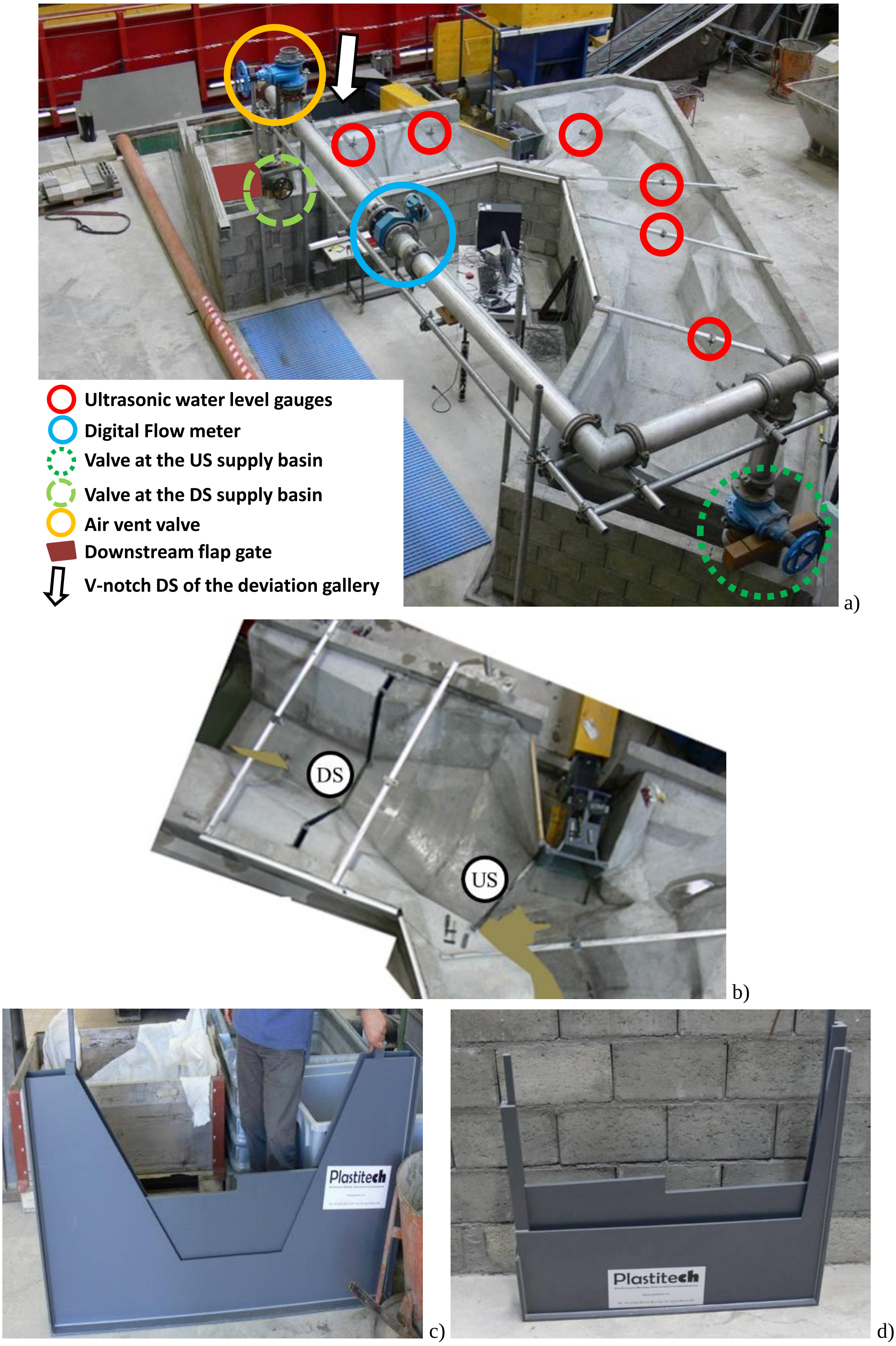

Figure 2: Picture of the physical model constructed at the LCH with its main operational elements (a), the two sill positions (b) as well as the adjustable downstream DS (c) and upstream US sill (d)

Two distinct sill positions were tested; the upstream (US) sill touches the right bank limit of the intake structure, whereas the downstream (DS) sill is located some 68 m downstream, perpendicular to the river axis. Both sills have two distinct crest levels, the right one (in river flow direction at outer bank in the bend, side of the SBT intake) is always 2 m higher, the elevation changes at the central axis of the sill.

6 Validation and optimization

6.1 Test runs

6.1.1 Clear water tests with sill

In a first step, clear water tests were performed to validate the discharge capacity, to obtain water level profiles as well as local velocity measurement for all potential operational modes. The test variables were the gate openings, two different sill positions and two sill elevations, different upstream river discharges (50, 100, 200 and 400 m^3/s, the last one corresponds to a 5-year return period flood), and two different reservoir water surface levels (1’445 and 1’450 m asl). Hydraulically the intake operates as expected from desk design and rating curves for all operational modes could be established. The approach flow conditions were investigated, with and without sill at both positions.

6.1.2 Run with bed load, no SBT operation, nor sill

In order to reproduce the natural behavior of the river in the model (e.g. during reservoir drawdown), the inlet gates were completely closed and there were no sills in the river. The potential deposition zones in the river were identified. Around 50 kg of sediment (model scale) were introduced at the upstream of the river with a discharge slightly higher than the one required for bed load transport initiation. After about one hour (model scale) the river found its equilibrium (no more erosion or deposition). Apart from minor deposits at the end of the model and inside the bend, there is practically no deposit downstream of the inlet structure. This observation is in accordance with the river slope, flow regime, grain size distribution and critical shear stress.

6.1.3 Run with bed load, SBT operation, with sill

Tests with sediment were performed for two different incoming discharges to verify the system efficiency for floods with different return periods. Both sill positions at two different sill levels were tested. Sediment was fed continuously. Once the sediment level attained approximately the lower elevation of the sill, the SBT inlet gates were completely opened. The reservoir water level was kept at 1’445 m asl by introducing an additional discharge from downstream to compensate the outgoing discharge through the bypass. The test duration was about 4 to 5 hours at model scale, which corresponds to one day at prototype scale.

6.2 Test results for SBT operation

After each simulated flood events, sediment samples from the model were assessed: volume evacuated through the SBT, volume deposited downstream of the sill (i.e. the potential inflow to the reservoir) and volume of the deposits upstream of the sill. This allows estimating the efficiency of the sediment bypass structure (Figure 3).

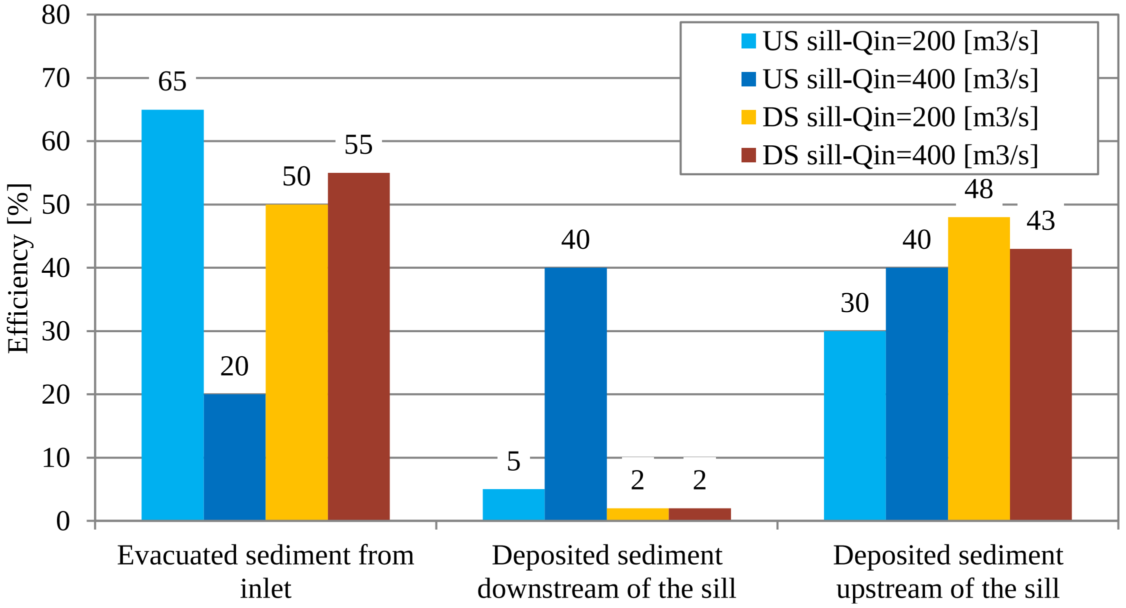

Figure 3: Efficiency for downstream sediment transfer corresponding to the four tested configurations. Ratio of deposited volumes regarding total sediment input for given test configurations

For the lower chosen discharge (200 m^3/s), the US sill performed best, bypassing some 65% of all incoming bed load downstream. When doubling the discharge, this value drops to 20%; in fact, most of the bed load passes the sill entering therefore into the reservoir. The DS sill performs generally much better and independently of the discharge. For all tested configurations, the amount of sediment retained upstream of the sill is similar for both sill locations, the DS sill having more space for deposits between the SBT intake and the sill. For lower discharges, that are getting close to the bed load motion limit, upstream drawdown flushing is required to transfer the sediment.

6.3 Final retained geometry

In conclusion, the sill at the downstream position allows for at least a 50% flushing efficiency whatever the discharge tested. On the other hand, the sill at the upstream position functions at 70% efficiency for a 200 m^3/s flood event. It should be reminded that the flushing efficiency term is used to assess the amount of the evacuated sediment by the bypass gallery. However, the upstream sill plays a significant role in preventing reservoir sedimentation. As the flushing process should be efficient for frequent flood events and not necessarily for extreme flood events, and taking into account the possibility of using the reservoir water for cleaning the area in front of the SBT inlet, the upstream sill works better than the downstream one. Therefore, based on the obtained results the retained configuration would be the upstream sill with a crest level at 1’444-1’442 m asl (variable across the valley width, see Figure 2c and 2d). This configuration leads to better sediment flushing and less deposition in front of the bypass inlet. To prevent the remaining sediment to enter the reservoir, reverse flushing from the reservoir should be performed.

6.4 Principles for future SBT planning, design and operation

For future operations as well as for studies on similar schemes with SBT leading to some Best Practice Guide, among others, the main following procedures should be considered:

- Selection of inlet location, elevation and orientation by respecting the river geometry, past and future rating curves and the reservoir storage curve;
- Evaluation of the need for a weir separating the SBT inlet from the reservoir, design, position, orientation and elevation of the structure;
- Choice of hydraulic design and operating regimes, for target bypassing capacity and operation frequency;
- Evaluation of target sediment grain size distribution and volumes (bed load and suspended load) with regard to total sediment yield, acceptable reservoir storage loss and sediment flushing and venting capacity of other hydraulic structures such as bottom outlets and power intakes;
- Review of tunnel design respecting topography, hydraulics, sediment transport capacity, lining material (mainly for invert and side walls) and outlet design (e.g. position, elevation, orientation, geometry with regards to the downstream river reach, rating curves and location of other infrastructure such as the powerhouse or bridges);
- Planning of a operation follow-up, instrumentation and monitoring to guarantee proper collection of operation data, efficiency rating, damage observation, etc.;
- Assessment of economic feasibility and continuous need, as well as of the corresponding ecological benefits derived from limiting the reservoir’s trap effect on the river ecosystem bed load budget.

7 Conclusions

A physical model at a scale of 1:38 has been built at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). The hydraulic design was validated by the laboratory experiments. The sediment bypass concept was optimized by selecting the best position of the sill. The upstream sill position was retained as it works satisfactory for most flood discharges.

7.1 Contribution of the bypass system

Without the bypass system the reservoir would be filled up within less than 10 years of operation. To mitigate such process, flushing operations through the bottom outlet of the dam with a reservoir drawdown could be carried out, leading to plant stoppage and loss of water and revenues. The sediment bypass system is an incremental project cost (capex) but avoids future expenses (opex) or production losses (reduced revenues). It guarantees the long-term availability of the live storage and production, thus liberating future cash flows for debt reimbursement and investment remuneration. The cost of the bypass system (including interests) is estimated as being approximately one order of magnitude lower than the total costs for palliative sediment flushing with reservoir drawdown over the expected project lifetime (considering the water losses and provision of replacement energy).

7.2 Contribution of the physical model tests

The physical model tests allowed validating the preliminary desk design, as well as optimizing the structures and the operational concept. First, the hydraulic conditions and by pass relations were validated for varying reservoir water levels. The location of the submerged diversion weir was revised, increasing the flushing efficiency for the most important operational scenarios. The foreseen operational guidelines were optimized, leading to the establishment of four different modes of operation, each with specific constraints and operational principles. In summary, the goals to improve sediment flushing efficiency while reducing production stoppage time and water losses has been achieved in laboratory conditions, allowing facing the reality of prototype implementation and scheme operation with reduced uncertainty regarding the reduction of live storage and production revenues.

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