



Efficiency evaluation of Swiss Sediment Bypass Tunnels

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Abstract

Sediment Bypass Tunnels (SBTs) are an effective measure against reservoir sedimentation. In the present study, we evaluate the Bypass Efficiency (*BE*) of three Swiss SBTs based on measured or numerically simulated hydraulic conditions and sediment transport data. The *BE* is defined as the ratio of bypassed sediment volume to inflowing sediment volume. The studies were conducted at Pfaffensprung, Runcahez and Solis SBTs. The first two SBTs have an intake at the reservoir head (type (A)), while the latter has the intake within the reservoir (type (B)). The *BE*s of both Pfaffensprung and Runcahez SBTs were high, i.e. 98% and 83%, respectively, in agreement with typical values for comparable SBTs. On the contrary, the Solis SBT exhibited a low *BE* of 31%. The monitoring data from the Solis SBT indicate that the *BE* strongly depends on the operational regime of both the SBT and the reservoir. Therefore, to potentially increase the *BE*, the SBT and reservoir operations need to be coordinated and optimized, which requires a continuous and real-time monitoring of the hydraulic and sediment transport conditions in the river, reservoir and SBT.

Keywords: Sediment bypass tunnels, bypass efficiency, reservoir operation, hydraulic monitoring, sediment transport monitoring

1 Introduction

SBTs divert sediment-laden flows to the downstream river reaches without deposition in the reservoirs. There are two types of SBT designs based on the intake location. Type (A) has the intake at the reservoir head, while type (B) has it within the reservoir (Boes *et al.*, 2019). The intake locations significantly affect the SBT and reservoir operations and the reservoir Bypass Efficiency (*BE*), i.e. the ratio of outflow sediment volume to inflow sediment volume. The *BE* in turn greatly affects the reservoir lifetime (*RL*), i.e. the period until a reservoir is arithmetically fully filled with sediment. *RL* is the ratio of the reservoir volume (*CAP*) to the mean annual sediment inflow volume (*MAS*), i.e. $RL = CAP/MAS$ (Auel *et al.*, 2016, Boes *et al.*, 2018). Determination of the *BE* and its influencing parameters are of prime importance for the design and operation of not only current but also future SBTs. Despite a few well-documented studies from Japan and observations from Swiss SBTs (Boes *et al.*, 2018), there is still a lack of systematic field investigations on the *BE* of existing SBTs. To fill this knowledge gap, we have conducted field studies at three Swiss SBTs and quantified their *BE*s. In the following, a brief literature

information is given, the Swiss case studies are described, and the results, discussions and conclusions are presented.

Auel *et al.* (2016) reported that since the first operation in 1998, the *BE* of Asahi SBT was 77% resulting in a prolongation of the reservoir life time by approx. 3.3 times. Furthermore, Sumi *et al.* (2004a, b) and Auel *et al.* (2016) reported the highest *BE* for Nunobiki SBT in Japan with 81% (1908-1939) and 95% (1939-1989), which is attributed to the effects of upstream Sabo dams trapping sediments. Another well-investigated SBT in Japan is the Miwa SBT. The studies showed that up to 80% of the total sediment inflow was bypassed between 2006 and 2011 (Sumi *et al.*, 2004b, Sumi *et al.* 2012).

In contrast to Japan, sediment monitoring at the Swiss reservoirs is limited to bathymetric observations and flushing monitoring. Despite this, the published data still give indications on the performance of a few Swiss SBTs. The Egschi and Palagnedra STBs, both located in the Swiss Alps, have performed well and significantly reduced reservoir sedimentation (Vischer *et al.*, 1997). Furthermore, Pfaffensprung SBT exhibits a *BE* of above 90% (SBB, 2015).

2 Case Study SBTs

2.1 Pfaffensprung SBT

The type (A) Pfaffensprung SBT is located in the Swiss Alps, featuring a catchment area of 390 km². The tunnel is 282 m long, has a design discharge capacity of 220 m³/s in free-surface flow and is in operation around 100 to 200 days per year on average (Fig. 1, Müller-Hagmann, 2017). The SBT cross-section is horse-shoe shaped and the longitudinal slope is 3%, except for the 25 m long acceleration section at the inlet with a slope of 35%. The Reuss River feeds the reservoir.

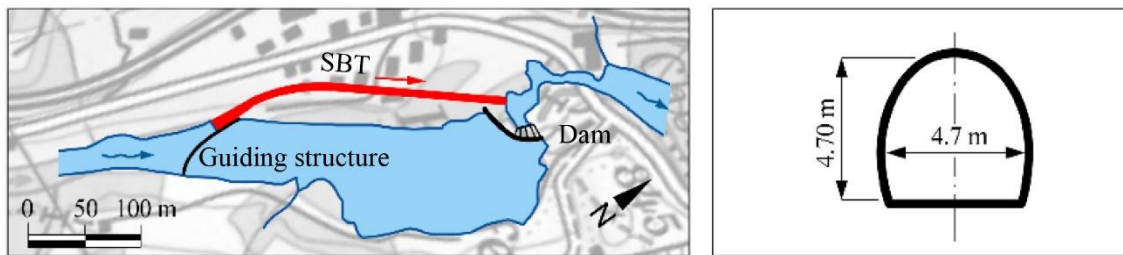


Figure 1: Overview and tunnel cross-section of the Pfaffensprung SBT (adapted from Müller-Hagmann, 2017)

Continuous sediment monitoring does not exist at the Pfaffensprung Reservoir and SBT, but the sediment volumes deposited in the reservoir are monitored and removed by flushing and excavation once a year. Therefore, the *BE* of the SBT was determined based on the estimated annual sediment transport masses in the Reuss River and the measurements of the annually removed sediment (Müller-Hagmann, 2017). The ratio of

suspended sediment load to bedload ratio in comparable Alpine Regions varies between 1:15 (Rickenmann, 2001) and 1:0.8 (VAW, 1992) and was assumed to be 1:1 in this case.

2.2 Runcahez SBT

The Runcahez dam was built in 1962 with a storage capacity of $0.44 \cdot 10^6 \text{ m}^3$ in the Eastern Alps of Switzerland. A 572 m long type (A) SBT was constructed and put in operation at the same time to mitigate reservoir sedimentation (Fig. 2). The SBT has an archway-shaped cross-section and the bed slope and design discharge amount to 1.4% and $110 \text{ m}^3/\text{s}$ in free-surface flow, respectively (Fig. 2). The Rein da Sumvitg River feeds the reservoir. The SBT is in operation during flood events for a few days per year if the river discharge exceeds $35 \text{ m}^3/\text{s}$ (Jacobs *et al.* 2001).

No discharge measurements are available from the reservoir, SBT and the river. Therefore, the hydrographs of the river were determined by scaling the measurements of a neighboring gauging station at Encardens (Müller-Hagmann, 2017).

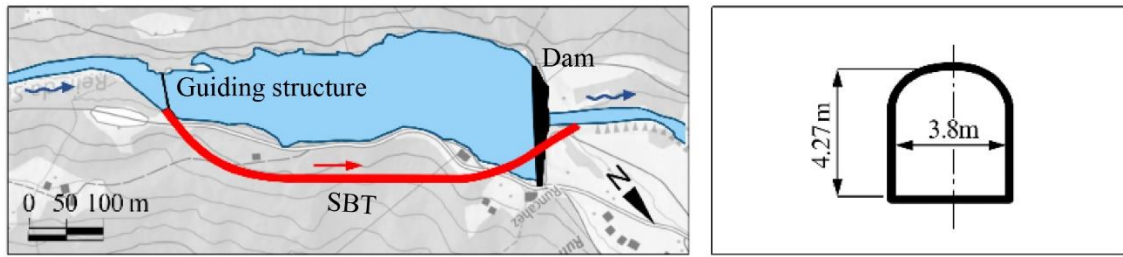


Figure 2: Overview and tunnel cross-section of Runcahez SBT (adapted from Müller-Hagmann, 2017)

2.3 Solis SBT

The Solis reservoir was commissioned in 1986. Its initial storage volume amounted to approx. $4.07 \cdot 10^6 \text{ m}^3$ of which $1.46 \cdot 10^6 \text{ m}^3$ (active volume) are used for power generation at the two downstream hydropower plants (HPPs) Sils and Rothenbrun by the electric power company of Zurich (ewz). The Albula River and the tailrace water of the upstream ewz HPP Tiefencastel feed the reservoir. Until 2008, 25% of the reservoir storage capacity was lost due to sedimentation. To reduce sedimentation and restore the interrupted sediment transport in the river reach, a 1 km long type (B) SBT was commissioned in 2012 (Fig. 3). The SBT has an archway cross-section with a slope of 1.9%. Its intake structure is situated well below the reservoir drawdown level just downstream of the delta front location at the time of the SBT construction to stop the advancement of the latter towards the dam. The inflow is therefore pressurized in normal SBT operation. The Solis SBT is typically put in operation at approach flow discharges exceeding some $90 \text{ m}^3/\text{s}$ (representing a one-year flood discharge) to bypass incoming sediments (Auel *et al.*, 2011).

The discharges in the Rivers Albula and Julia are continuously monitored by the Swiss Federal Office for the Environment (FOEN) at gauging stations in Tiefencastel. The fine

sediment and bedload transports from the River Julia to the reservoir are negligible due to the desilting effect of two upstream reservoirs (Müller-Hagmann, 2017). Therefore, incoming Suspended Sediment Concentrations (SSC) are only measured in the Albula River by FOEN using a turbidimeter. Furthermore, bedload transport in this river is monitored using a Swiss Plate Geophone System (SPGS) installed 500 m upstream of the FOEN station (Rickenmann *et al.*, 2017, Albayrak *et al.*, 2017).

Fine suspended sediment can be released from the reservoir by the SBT, the headraces of the HPPs Sils and Rothenbrunnen, the bottom outlet, the spillway and the environmental flow through a small turbine at the foot of the dam. Quantification of outflow SSC is described in Müller-Hagmann (2017). Incoming bedload can be released from the reservoir by the SBT and/or the bottom outlet. The bedload transport through the latter is negligible. The bedload transport in the Solis SBT is monitored using the SPGS installed at the outlet of the SBT (Albayrak *et al.*, 2017). The *BE* was determined by computing the mean annual sediment inflow, excavated material and outflow volumes (Müller-Hagmann, 2017).

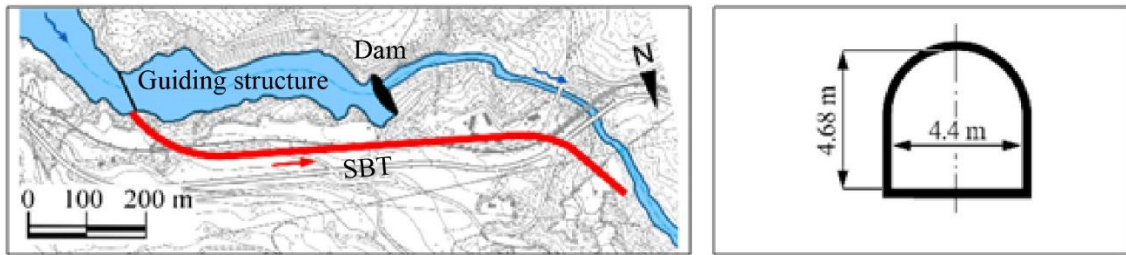


Figure 3: Overview and tunnel cross-section of Solis SBT (adapted from Müller-Hagmann, 2017)

3 Results & Discussions: Bypass Efficiencies

3.1 Pfaffensprung SBT

The mean annual operation duration of the Pfaffensprung SBT (type (A)) was 118 days per year, bypassing a mean discharge of $Q_{SBT} = 7.4 \text{ m}^3/\text{s}$ between 2012 and 2015. The mean annual volumes of inflowing and outflowing fine sediment were $350 \cdot 10^3$ and $337 \cdot 10^3 \text{ m}^3/\text{yr}$, respectively, while the mean annual volumes of inflowing and outflowing bedload were $350 \cdot 10^3$ and $350 \cdot 10^3 \text{ m}^3/\text{yr}$, respectively. This result leads to a reservoir *BE* (accounting for all sediment) of 98%, and a bedload *BE* of 100%.

3.2 Runcahez SBT

The mean annual operation duration of the Runcahez SBT (type (A)) was 1.5 days per year, bypassing a mean discharge of $Q_{SBT} = 56 \text{ m}^3/\text{s}$ between 1996 and 2014. The mean annual volumes of inflowing and outflowing fine sediment were $10.6 \cdot 10^3$ and $7.1 \cdot 10^3 \text{ m}^3/\text{yr}$, respectively, while the mean annual volumes of inflowing and outflowing bedload were $10.6 \cdot 10^3$ and $10.6 \cdot 10^3 \text{ m}^3/\text{yr}$, respectively. This result leads to a total *BE* of 83% and a bedload *BE* of 100%.

3.3 Solis SBT

The mean annual operation duration of the Solis SBT was only 21.3 hours/yr averaged over 9 SBT operations, bypassing a mean discharge of $Q_{SBT} = 99 \text{ m}^3/\text{s}$ between 2013 and 2016. This operation duration is below the typical operation durations of type (A) SBTs. The mean annual volumes of inflowing and outflowing fine sediment were $90.7 \cdot 10^3$ and $32.9 \cdot 10^3 \text{ m}^3/\text{yr}$, respectively, while the mean annual volumes of inflowing and outflowing bedload were $16.8 \cdot 10^3$ and $0.4 \cdot 10^3 \text{ m}^3/\text{yr}$, respectively. This result leads to a total BE of 31%, which is relatively low compared to other reservoirs with a type (A) SBT in operation exhibiting $BE = 60 - 90\%$. The bedload BE amounted to 2%.

3.4 Discussions

Despite completely different operation durations of more than 100 days versus approx. 1 day per year, the BE s of Pfaffensprung and Runcahez SBTs are high, which are in agreement with typical values for type (A) SBTs. However, the BE of Solis SBT is considerably lower with 31%, because of the different characteristics of a type (B) SBT. Bathymetric data of Solis reservoir indicate temporary sediment deposition, which affects the BE . Furthermore, the continuous bedload, suspended sediment load and hydraulic monitoring data show that the BE strongly depends on the operating regime of the SBT and reservoir. The sediment transport rates in Solis SBT increase with decreasing reservoir water level and increasing approach flow discharges (Müller-Hagmann, 2017). This is related to increasing flow velocities and hence bed shear stresses for a given discharge at low reservoir water levels compared to high reservoir levels. Furthermore, the amount of bypassed sediment increases with operation duration. Such monitoring data highlight the importance of the coordination and optimization of the SBT and reservoir operations to achieve high BE of type (B) SBTs.

4. Conclusions

The bypass efficiencies of three Swiss SBTs were evaluated based on the measured or numerically simulated hydraulic conditions and sediment transport data. Pfaffensprung and Runcahez SBTs are of type (A) with the intakes located at the respective reservoir head, while Solis SBT is of type (B) with the intake within the reservoir. The BE s of Pfaffensprung and Runcahez SBTs were high, whereas the BE of Solis SBT was significantly lower. The present results indicate that the BE strongly depends on the SBT intake location and the operational regime of both the SBT and the reservoir. Therefore, to potentially increase the BE , the SBT and reservoir operations need to be coordinated and optimized, which requires a continuous and real-time monitoring of the hydraulic and sediment transport conditions in the river, reservoir and SBT.

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