Solis sediment bypass tunnel: First operation experiences

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Abstract

The Solis dam was built in 1986 by the Electric Power Company of Zurich (ewz). Ever since the construction, large amounts of sediments accumulated in the reservoir and led to severe sediment aggradation. As a consequence, the storage volume was reduced by about 50% till 2012 causing loss of energy production. Additionally, in the near future sediments may have caused severe damage at the dam due to blockage of the bottom outlets. Therefore, in 2011 and 2012 a sediment bypass tunnel was realized in order to redirect the incoming sediments into the tailwater to inhibit sediment aggradation. Since its inauguration, the tunnel was operated four times including a 100-year flood event in August 2014. First operational experiences are described herein.

1 Introduction

The Solis reservoir, built in 1986 by ewz, is located in the canton of Grisons in the south-eastern part of the Swiss Alps. The reservoir is retained by an arch dam of 61 m height with a crown length of 75 m. The reservoir is fed by the turbined water of the upstream power plants Tiefencastel Ost and West as well as the Albula and Julia River. The reservoir itself provides the water supply for the two power plants Sils and Rothenbrunnen taking the function of a daily storage.

The original volume of the reservoir was 4.1 million m^3 with an active storage volume of 1.5 million m^3. The reservoir is operated between the minimum level of 816 m a.s.l. and the full supply level of 823.75 m a.s.l. according to the active volume range.

Due to the large catchment area of 900 km^2, an average annual amount of 80'000 m^3 sediment material accumulated in the reservoir. The narrow topology of the reservoir caused a one-dimensional sediment aggradation process progressing towards the dam. From 1986 to 2008 the sediment aggradation caused a decrease of the active storage of 1.0 million m^3 (Auel *et al.* 2011). Figure 1 illustrates the annual aggradation of the reservoir obtained by echo-sounding surveys. In 2012, about half of the original reservoir volume was filled with sediments.

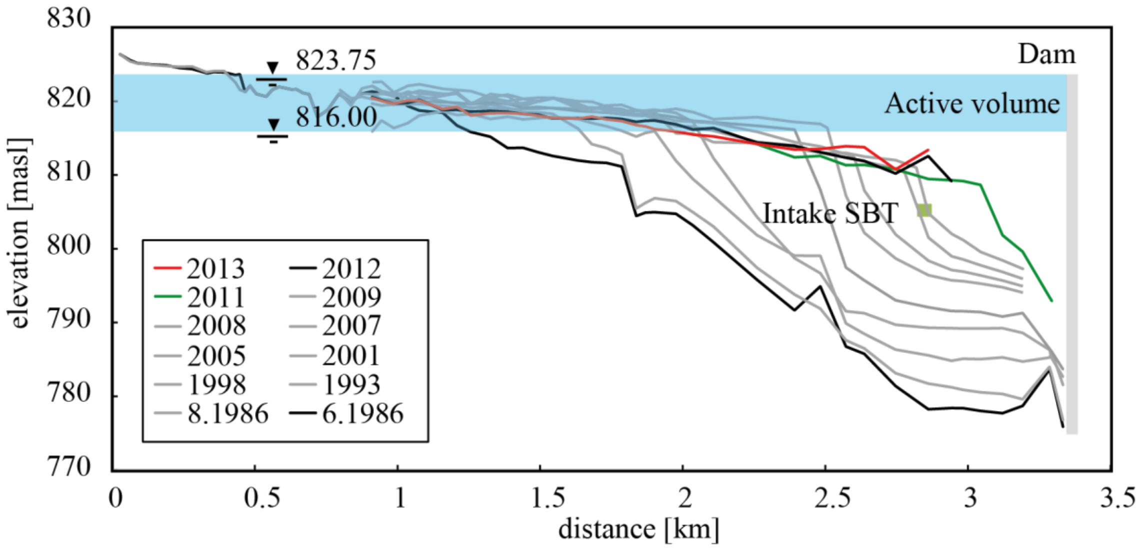

Figure 1: Sedimentation at Solis reservoir (courtesy of M. Hagmann)

2 Feasibility study of countermeasures

The sediment aggradation derogated an economical operation of the hydropower plants and endangered the operational safety of the bottom outlets. Different alternatives were studied in order to avoid these negative impacts and restore the active storage volume. Strategies such as dredging, free surface flushing, sluicing and bypassing through a tunnel were considered (Auel *et al*. 2010, Auel *et al.* 2011). Mechanical dredging turned out to be inappropriate due to both ecological and economic reasons. Flushing sediments through bottom outlets in free surface flow was not considered as an effective countermeasure as well because of the low capacity of the bottom outlets. Another problem was the financial loss due to a complete reservoir drawdown and the resulting plant shutdown. Furthermore having in mind that flushing has to be done during natural flood events emerging rapidly, reaction time would be short for a complete drawdown.

Partial drawdown sluicing and bypassing through a tunnel seemed to be adequate strategies and have been examined in hydraulic model tests at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich (Berchtold and Lais 2008, Auel *et al.* 2010, 2011). Sluicing sediments through the bottom outlets resulted in both a funnel-shaped cone in the bottom outlet vicinity and an entire degradation of the aggregation body throughout the reservoir. The extent of the degradation depended on both the inflow discharge and the level drawdown magnitude. The sluicing process lead to a relocation of the already aggregated sediments towards the dead storage and allowed the newly incoming sediments to be guided through the reservoir into the tailwater. Thus, the model tests showed that sluicing is an effective strategy to keep the active volume free from sedimentation (Berchtold and Lais 2008). However, some drawbacks were emphasized. The bottom outlets are small and likely prone to blockage by driftwood and mudslides of fine sediments. Additionally severe abrasion in the outlets was expected and safety concerns arose due to the fact that the closing process of the gates could be inhibited by clogging sediment.

Besides the sluicing technique, a sediment bypass tunnel (SBT) was studied to guide the incoming sediments into the tailwater (Auel *et al.* 2010, 2011). The tunnel was not located at the reservoir head as mostly applied worldwide (Auel and Boes 2011), but located about 450 m upstream of the dam. Consequently the bypass only minimizes sedimentation in the lower reservoir part. Similar to the sediment sluicing, the reservoir level is partially lowered to obtain free surface flow conditions at the upper reservoir forcing sediment transport towards the intake. The model results showed that the tunnel bypasses all incoming coarse sediments independent of the flood discharge. However, if the design discharge is exceeded, a surplus flow passes the tunnel intake and leads parts of suspended sediments to the front of the reservoir. Blockage of the tunnel intake was considered as less likely compared to the bottom outlet sluicing as the area of the tunnel was 4.3 times larger. Additionally, blockage due to driftwood was minimized by adequate structural measures guiding the material towards the dam.

For a sound comparison of the two strategies ewz quantified the economic benefits of both methods having in mind that the larger the active volume the higher the benefit. The key parameters to obtain an active volume free from sediment deposition are the incoming discharge and water level drawdown regardless of the routing technique. Hence, sluicing and bypassing are identically considered as an effective measure to keep the active volume free from sediments. In a second step, the risk probability of both strategies, i.e. the blockage of the bottom outlets or the tunnel intake, was quantified and compared with the costs (Oertli 2009). On the one hand sluicing sediments through the bottom outlets caused higher risks but showed better profitability whereas flushing sediments through a bypass tunnel caused lower risks at a lower profitability. Sluicing included a number of high risks which may lead to a complete plant shutdown over a long period, while flushing through a tunnel shifted these risks to a new structure upstream and away from the dam and power intake vicinity.

The total cost of the SBT amounted to 37 million CHF being about 18 million CHF more expensive as estimated. The annual costs for maintenance and repair were estimated to 880’000 CHF. This value seems to be conservative from today’s perspective as the invert abrasion is low so far (Hagmann *et al.* 2015). The alternative sluicing strategy through the bottom outlets would have caused investments of only about 2.0 million CHF and annual costs for maintenance and repair of 350’000 CHF. Additionally, the above described high risks of the bottom outlet sluicing were transferred to equivalent monetary costs leading to the situation that both strategy costs were almost identically rated. Moreover, Solis reservoir is an important power hub between other ewz HPPs up- and downstream, so that a shutdown would affect power production of a number of plants. Therefore, ewz decided to choose the sediment bypass tunnel as countermeasure.

In Europe, energy is traded at the European Energy Exchange in Leipzig, Germany (EEX). The presented economic calculations and decisions were mostly based on energy prices in 2008. As the market-based price for electric power in Europe significantly decreased since then (Figure 2), the comparison would probably lead to a different result today.

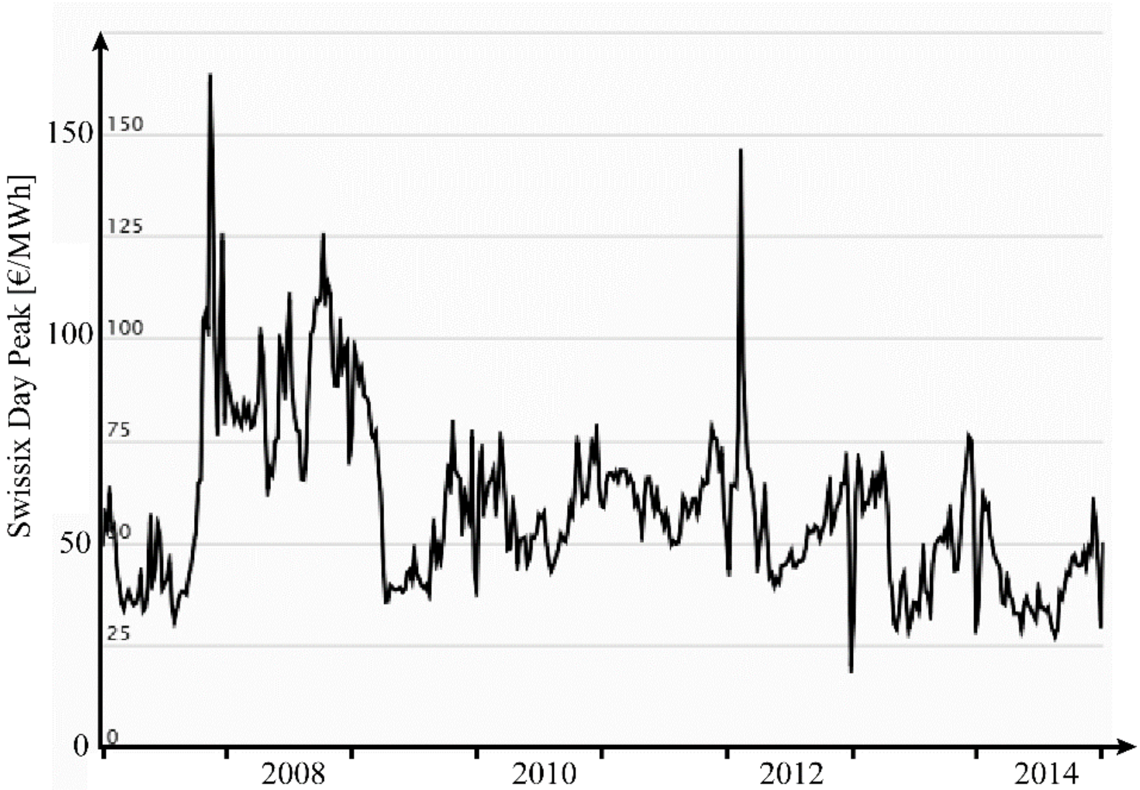

Figure 2: EEX *Swissix Day Peak* price from 2007 to 2014 (www.eex.com)

3 Sediment bypass tunnel design

The SBT design was developed in close collaboration with VAW of ETH Zurich (Auel *et al.* 2010, 2011). The tunnel was constructed from 2011 to 2012 and consists of the components described in the following (Figure 3). A 140 m guiding structure crosses the reservoir from the left to the right bank and leads the sediment laden inflow to the inlet structure. The tunnel intake is located around 450 m upstream of the reservoir on the right bank and not at the reservoir head. Consequently, the water enters in pressurized inflow conditions with a maximum energy head of about 20 m at maximum reservoir level. However, the reservoir is lowered prior a flood event leading to free flow conditions upstream of the intake and provoking the sediment to be transported towards the tunnel. The minimum reservoir level of the active volume (816 m a.s.l.) was defined as the standard for flushing events (Figure 4).

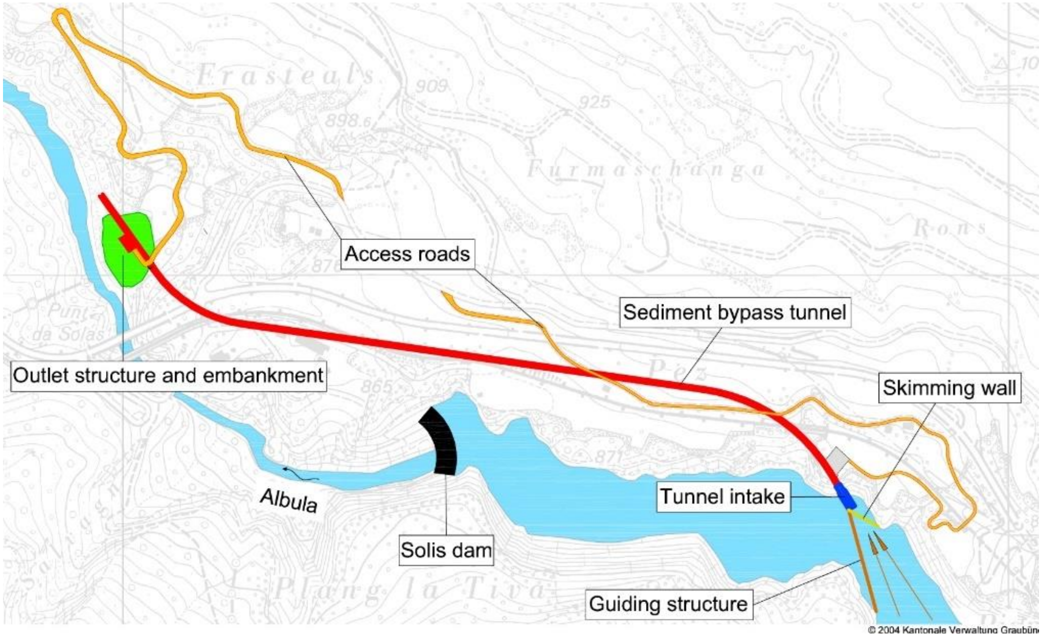

Figure 3: Overview of Solis sediment bypass tunnel (adopted from Auel *et al.* 2011)

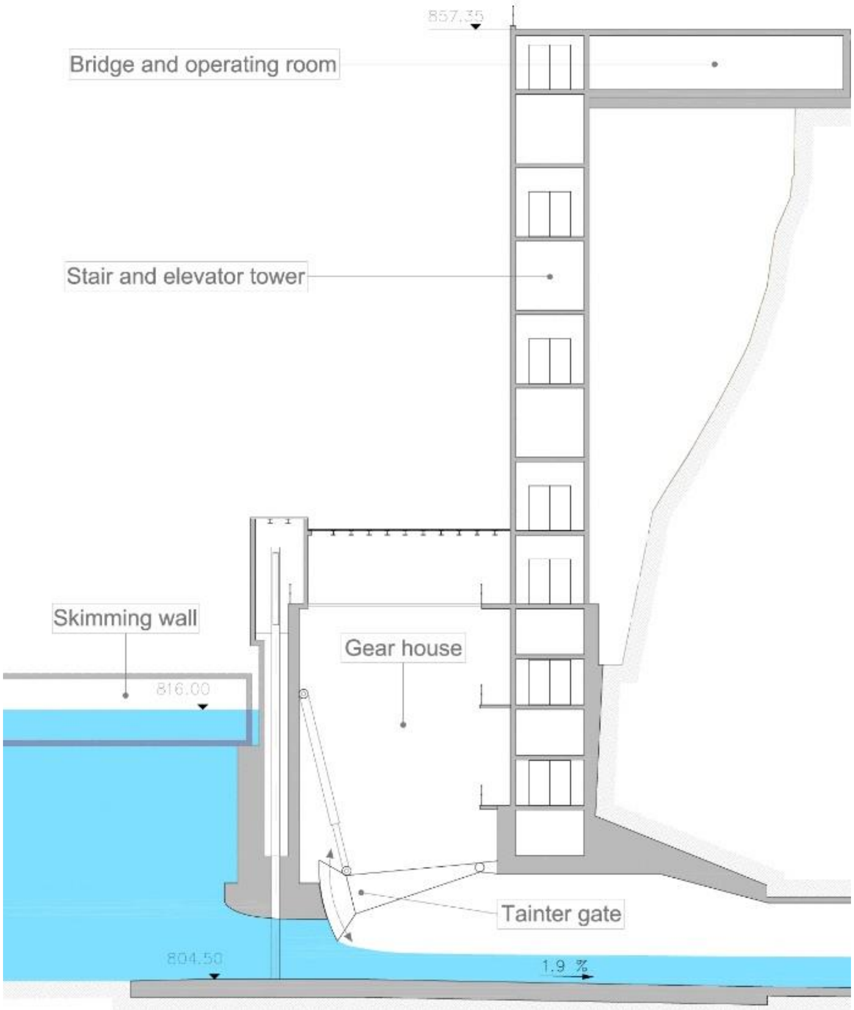

Figure 4: Detail of tunnel intake (adopted from Auel *et al.* 2011)

However, the upstream erosional effect is substantially higher for lower levels. Depending on the future conditions, bypassing with lower levels (e.g. 814.5 m a.s.l.) may be considered. The design capacity of the tunnel is $Q_d = 170$ m^3/s (flood event occurring approximately once in 5 years). A tainter gate regulates the inflow into the tunnel. Stop logs located in front of the gate are used for revision.

In case of high floods exceeding the design tunnel discharge, a partial flow is guided towards the dam trough an opening in the guiding structure. Additionally as skimming wall guides incoming driftwood safely towards the dam, where it is mechanically removed or flushed over the spillway (Figure 5). These facilities were optimized in the hydraulic model tests described in Section 2 (Auel *et al.* 2010, 2011).

(a) (b)

Figure 5: (a) Tunnel intake with tower in November 2012. View from left bank. Reservoir level at approx. 820 m a.s.l. (b) Detail of guiding structure during bypass operation at May 3rd 2013. Reservoir level at approx. 816 m a.s.l. (courtesy of ewz)

The total length of the tunnel including the intake and outlet is 968 m with a constant bed slope of 1.9%. The cross section is constructed as an archway type with a width of 4.40 m and a height of 4.68 m. The invert is concrete lined using an abrasion-resistant high performance concrete with a compression strength $f_c \geq 70$MPa (Hagmann *et al.* 2015). Downstream of the dam, the water is released through a 100 m long cantilever outlet structure and drops about 8 m into the Albula River (Figure 6).

Figure 6: Cantilevering tunnel outlet during operation on May 23rd 2014 (courtesy of C. Auel)

4 Measurements at Solis reservoir

The Solis reservoir is equipped with a range of devices measuring the in- and outflow as well as the sediment load. Discharge is measured at gauging stations in the Albula and Julia River operated by the Federal Office of the Environment (FOEN). Also the discharge released by the upstream HPP Tiefencastel West and Ost is known, thus the total inflow into Solis reservoir is precisely predictable. The outflow consists of the turbined water at Rothenbrunnen and Sils as well as the bottom outlet, spillway and bypass tunnel discharges in case of flood events. All values are recorded by ewz.

Suspended sediment load is measured using turbidity meter at Albula gauging station upstream of the reservoir and downstream of Sils HPP in the tailrace channel. Additionally, suspended and bedload are measured in the bypass tunnel using geophones for the latter (Hagmann *et al.* 2015).

Finally, reservoir sedimentation is surveyed almost every year using echo sounding (compare Figure 1).

5 First tunnel operation

The sediment bypass tunnel operated for the first time on May 3rd 2013 in order to divert a minor flood during the snowmelt period. A maximum discharge of 110 m^3/s was routed through the tunnel during 12 hours runtime in total. As a result, sediment aggradation upstream of the intake was levelled to a homogenous gradient of 3.8‰ and sediment was shifted closer to the inlet structure. The net sedimentation increase upstream of the intake was about 10’700 m^3 compared to the survey prior the flood event. This increase was expected as the bed level of the upstream reservoir part had to adapt to the new flushing conditions with a low reservoir level.

After a further minor flood in spring 2014, a 100-year flood event occurred on August 13th 2014 in the Albula River. A maximum discharge of 288 m^3/s was recorded, of which 179 m^3/s were routed through the sediment bypass tunnel. Mastering this event with a new bypass facility was a challenge for the task force team. At the same time, a train derailed close to the reservoir head and was in danger to slide into the reservoir. Thus the reservoir level had to be lowered between 814 and 816 m a.s.l. due to police instructions. The tunnel operation lasted 14 hours in total.

Sedimentation in the reservoir increased by approximately 102’000 m^3. At a similar flood event in 1987 with a comparable maximum inflow of 252 m^3/s, sedimentation increased by 248’000 m^3. The comparison between the two flood events in 1987 and 2014 shows that a large amount of sediments was routed through the sediment bypass tunnel. Further details regarding the bypassed sediments are published in Hagmann *et al.* (2015).

6 First operator impressions

So far the sediment bypass tunnel masters the flood events impeccably without any technical problems. The hydraulic system, the abrasion-resistant invert lining and the driftwood diversion function particularly well. Based on the hydraulic model experiments, the intake and guiding structure are designed well. All facilities operate as described in the experiments.

An optimal SBT operation requires a sufficient preliminary lead time. The reservoir level has to be lowered to 816.0 m a.s.l., different operation systems have to be taken into service, sediment concentration measurements have to be installed in the rivers and a number of specialists as well as auxiliary staff needs to be mobilised. Thus, the monitoring of the weather forecast is crucial. However, a reliable forecast is challenging as the effective rainfall in the catchment area is influenced by both the southern and northern meteorological conditions.

The head of operations takes the decision, if SBT operation is initiated. Due to the above-mentioned reasons, this decision needs to be taken as early as possible. However, a premature decision is prone to the risk of a cost-intensive and nerve-stretching operation cancellation in case the flood turns out to be minor. Therefore, a decision support system to simplify and sustain the decision-making process is of utmost interest.

A further important aspect of the tunnel operation is the energy management. If the reservoir is lowered below 816.0 m a.s.l., HPP Sils and Rothenbrunnen have to shut down. A short-term outage of a power plant leads to a considerable economic damage because alternative energy needs to be acquired on the energy stock exchange leading to high penalties for the operators due to guaranteed system services. Hence, the decision on which level the operation should be conducted also depends on the current market situation.

The current SBT operation is comparable to a *blind flight*. The only information at disposition are the gauging stations in rivers and the reservoir itself as well as the suspended sediment concentration measurements (Section 4). Thus it is very challenging to ensure an optimal operation based on only this information. The head of operations has to estimate both the operation duration and the amount of bypassed water while keeping the reservoir level preferably constant. The level is effected by the opening of the tunnel intake gate as well as the bottom outlet and HPP headrace tunnels. There is a substantial potential to waste water (and money) due to imprecise flushing operation.

It is planned to use the direct sediment transport measurements by geophones (Hagmann *et al*. 2015) as an additional information to provide detailed knowledge if sediment is still transported with the flow. This information is considered as very helpful as the effect of reservoir level variation can be directly correlated to change in sediment transport. So far, the recorded data is used by VAW but not included as a real-time measurement in the operation process.

7 Ecological aspects

The first five years of operation, i.e. until 2017, a concentrated ecological monitoring is conducted. In addition to the direct effects to the habitat in the tailwater, also the long-term and indirect effects of the flushing events will be measured, i.e. the invertebrate, river bed clogging and reproduction of the aquatic fauna. Today’s obvious lack of sedimentation will be replenished in the upcoming years. It is assumed that a natural habitat for flora and fauna will develop.

The following aspects directly affect the success of the ecological benefits. On the one hand it has to be ensured that the natural flood hydrograph as well as the sediment concentration can be maintained also downstream of the dam. Especially the sediment concentration of the declining flood has to be monitored considering a subsequent rinsing with clean water. On the other hand attention should be paid to the sediment concentration during reservoir drawdown prior the flushing process. The downstream sediment concentration should be limited and not reach unnaturally high levels: The limit for the average concentration is 40 mg/l, while short peaks can be higher.

In 2017, the results of this ecological monitoring will be analysed and definitive requirements regarding the operation of the sediment bypass tunnel will be elaborated.

8 Conclusion

The Solis sediment bypass tunnel operated well in the first two years after commissioning. However, sediment aggradation increased in the reservoir due to a 100 year flood event in summer 2014 exceeding the design capacity of the tunnel by about 40%. As a result the surplus inflow was diverted to the dam causing sedimentation of suspended load at the dam vicinity.

Certain organisational challenges arose in the first years showing that several more years of experience are still required to ideally operate the tunnel considering ecological, economical and operational aspects.

Moreover, the Solis sediment bypass tunnel is an excellent example for interdisciplinary collaboration. The positive cooperation between the academically-oriented specialists of ETH Zurich, the practice-oriented engineers and qualified HPP staff at ewz led to success of the design, construction and operation of the tunnel.

Acknowledgments

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