Dealing with Pelton turbine erosion based on systematic monitoring

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Hydro-abrasive erosion in hydraulic turbines is a well known problem, but comprehensive data sets from hydropower plants are still rare. Therefore, the sediment load, erosion depths and efficiency changes have been measured and evaluated since 2012 at a high-head run-of-river hydro plant in the Swiss Alps. An erosion model for hard-coated Pelton buckets was calibrated based on the data obtained. It is demonstrated that hydro plant shutdowns in periods of exceptionally high erosion potential are profitable. A procedure to estimate a site-specific threshold value of suspended sediment concentration for hydro plant shutdowns is proposed.

The geometric degradation on the splitter crests and the cut-out edges leads to disturbed flow patterns and less efficient energy transformation in the turbine. Brekke et al. [2002] stated that the turbine efficiency at full load drops by some per cent when the splitter width reaches some per cent of the inner bucket width. In practice, the splitter width is used as an indicator for the erosion status of a runner [Boes, 20099]. However, it is not the only parameter affecting the efficiency. For example, Hassler and Schnabegger [2009] related the efficiency reduction to the erosion on the cut-outs, including the radial position of the splitter tip.

Lower efficiencies, and potential downtimes as a result of damage and repairs, reduce electricity generation. In addition, erosion increases the costs for turbine refurbishment and spare parts. All in all, the energy efficiency and profitability of hydro plants are negatively affected by hydro-abrasive erosion.

To optimize the planning and operation of new and existing high-head hydro plants on sediment-laden rivers, there is a need for practical and reliable measuring techniques to quantify the sediment load, turbine erosion and efficiency changes, and improved knowledge on quantitative relations between these quantities, leading to practically applicable prediction models.

1. Research project

To address the issues mentioned above, the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich and the Competence Center for Fluid Mechanics and Hydro Machines of Hochschule Luzern initiated an interdisciplinary research project in 2011. After a preliminary laboratory investigation on various instruments for suspended sediment monitoring; numbers refer to Table 1. Modified from [Felix 2017]11.

Sediment-laden water causes hydro-abrasive erosion on turbines and pumps in hydropower plants. As a result of the relatively high flow velocities, Pelton turbines in high-head plants are particularly affected [Grein and Krause, 1994; Brekke et al., 2002; Bajracharya et al., 2008; Maldet, 2008; Guummer, 2009; Wedmark, 2014]. Special turbine designs and the application of hard-coatings (tungsten carbide in cobalt-chrome matrix, WC-CoCr) contribute to increasing the times between overhauls. In severe conditions, regular monitoring, repair and replacement of turbine parts are still required. Despite a large number of investigations on hydro-abrasive erosion for more than a century, it is difficult to predict the extent of erosion because of the complex interactions between the sediment particles, the flow and the turbine parts.

In uncoated Pelton buckets, hydro-abrasive erosion leads to a wavy and scaly surface inside the buckets, blunt splitters and deeper cut-outs [Rai et al., 2017]. In hard-coated buckets, only the two latter erosion features are typically observed, as long as there are no secondary damages caused by cavitation.

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plant in 1976, turbine erosion (Fig. 2b) has been an important issue. Since 2005, hard-coated runners, needle tips and needle tip rings have been in operation.

2. Measuring techniques and procedures

2.1 Suspended sediment monitoring

The suspended sediment concentration (SSC) and the particle size distributions (PSD) have been continuously measured at Fieschertal since 2012, using an innovative combination of techniques described in the following sections.

2.1.1 Gravimetric SSC from pumped water samples

The SSC is defined as the mass of particles per volume of water-sediment mixture. In the present study, SSC is expressed in grams per litre (1 g/l corresponds to 1000 ppm by mass). The most reliable technique to determine SSC is to measure the volume of a sample and weigh the dried particles in the laboratory. The collection, transport and analysis of water samples require a major effort. Despite this, the gravimetric technique is still the indispensable basis for the indirect techniques described in sections 2.1.2 to 2.1.5.

At Fieschertal, an automatic water sampler (see Table 1) has been installed in the valve chamber. The sampler is controlled by a local measurement computer to pump a sample every five days and more frequently at higher SSC. About 100 bottled water samples per year were taken, of which the SSC was gravimetrically determined in the laboratory.

2.1.2 SSC from turbidity measurement

Turbidimeters measure the attenuation or backscatter intensity of light resulting from suspended particles in the water. Turbidity values are converted to SSC using a correlation based on gravimetric reference SSC. The major drawback of turbidimeters is that their SSC output is biased if particle properties such as size, shape, density and colour vary over time independently of the SSC.

At Fieschertal, two submersible turbidimeters (CUS41 and CUS51D from Endress+Hauser) were installed in the river upstream of the intake and in the sand trap, respectively. In the valve chamber, a wall-mounted turbidimeter (see Table 1 and Fig. 3) was installed. This type of turbidimeter measures SSCs at a free-falling water jet and has the advantage of not requiring any cleaning.

2.1.3 SSC from acoustic attenuation

Ultrasound signals are used for suspended sediment monitoring in many ways. In this research project, an acoustic technique was used which enables measuring the SSC in the penstock without any additional sensors. This is possible by using a certain type of existing installation for acoustic discharge measurement (ADM, see Table 1 and Fig. 3). The acoustic pulses sent between the ADM transducers are attenuated by particles in the water [Costa et al., 2012]. This attenuation is converted to SSC based on gravimetrically determined reference SSC. In comparison with turbidimeters, this acoustic technique was found to be less sensitive to particle size variations. Similar to turbidimeters, this acoustic method provided SSC up to ~8 g/l of mainly fine and medium silt, depending on the PSD [Felix et al., 2018].

Table 1: Instruments for suspended sediment monitoring (modified from Felix [2017])

<table>
<thead>
<tr>
<th>Instrument type</th>
<th>Instrument model; Manufacturer</th>
<th>Instrument output(s)</th>
<th>Derived quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Automatic water sampler</td>
<td>Iso 3700; Iso-Teledyne</td>
<td>Bottled water samples (24 x 1 litre)</td>
<td>SSC</td>
</tr>
<tr>
<td>2. Turbidimeter (measuring at a free-falling jet)</td>
<td>AquaScat WTMA; Sigrist Photometer</td>
<td>Turbidity (at 90°) 0 to 6000 FNU</td>
<td>SSC</td>
</tr>
<tr>
<td>3. Acoustic discharge measurement (ADM) installation</td>
<td>Risonic Modular; Rittmeyer</td>
<td>Damping (0 to 1) at 1 MHz, 2.73 m path length</td>
<td>SSC</td>
</tr>
<tr>
<td>4. Coriolis flow- and density meter (CFDM)</td>
<td>Promass 83 FDN15; Endress+Hauser</td>
<td>Volumetric flow rate, density, temperature</td>
<td>SSC</td>
</tr>
<tr>
<td>5. LISST (laser in-situ scattering and transmittometry)</td>
<td>LISST-100X, Type C, with 90 per cent path reduction module; Sequoia Scientific</td>
<td>Volume concentrations (ppm) in 32 size classes (2 to 380 µm)</td>
<td>SSC and PSD</td>
</tr>
<tr>
<td>6. Pressure transmitters at u/s and d/s ends of penstock</td>
<td>Rosennount 2088, 1151; Emerson Process</td>
<td>Static pressure (0 to 55 bar)</td>
<td>SSC</td>
</tr>
</tbody>
</table>

Fig. 3: Setup for suspended sediment monitoring in the valve chamber of the Fieschertal scheme; numbers refer to Table 2. Modified from [Felix 2017].
2.1 Surveying of the current geometry of selected Pelton runner buckets inside the turbine housing at the Fieschertal scheme (Abgottspon et al., 2016).

2.1.4 SSC from density measurement
SSC can be monitored by measuring the density of the sediment-laden water (Bishwakarma and Stele, 2008). To this end, a Coriolis flow and density meter (CFDM) was installed at a sampling pipe fed from the penstock (see Table 1 and Fig. 3). In such an instrument, the fluid density is measured based on the resonance frequency of slightly oscillating tubes inside the instrument. With occasional offset correction based on reference SSCs, this technique was found to be suitable to measure SSC > 1.5 g/l [Felix et al., 2018].

2.1.5 SSC and PSD from laser diffraction
Laser diffraction has been used for decades to measure PSDs of particles in laboratories. More recently, portable and submersible instruments known as laser in-situ-scattering and transmissometry (LISST) have become available for in-situ measurements [Agrawal and Pottsmit, 2000]. LISST instruments yield both SSC and PSD. In contrast to turbidimeters and the acoustic method, variations of particle sizes are considered in the SSC output. Such an instrument was also installed at the sampling pipe in the valve chamber of Fieschertal (see Table 1 and Fig. 3). The SSC conversion was again adjusted to reference SSC to compensate for the effects of highly non-spherical particles and potential flocculation. With a reduced optical path length of 5 mm and no dilution, LISST provided results up to a few g/l of the usually prevailing silt particles or up to some 10 g/l for occasionally transported fine sand particles [Felix et al., 2018].

2.1.6 SSC from pressure measurements
Another technique to monitor SSC is based on pressure measurements at a fluid column at two levels with a known difference in elevation. This technique is applied at the penstock of Fieschertal. The headwater level and static pressure upstream of the turbines (see Table 1) are measured and evaluated with operation data (discharge) from the supervisory control and data acquisition (SCADA) system of the hydro plant. With sediment particles in the water, the pressure at the downstream end of the penstock is higher than that in clear water at given turbine discharges and headwater level. This technique allowed measuring SSC > 2 g/l in steady-state conditions [Felix, 2017].

2.2 Erosion monitoring
The erosion on the buckets of the Pelton runners was quantified by systematic coating thickness measurements and optical 3D-surveys before and after the sediment seasons. The measurements were conducted inside the turbine housings in the winter seasons when only one turbine was operated.

2.2.1 Coating thickness measurements
The local coating thicknesses inside two buckets per runner were measured using a hand-held coating thickness meter, based on magnetic induction (Deltascope FMP30 from Helmut Fischer AG, Germany) with a dual tip probe. The thickness meter was zeroed on an uncoated, even and smooth spot on the outer sides of the buckets. Then it was calibrated by placing a plastic sheet with a known thickness between the base material and the probe tip.

To define the locations of the measuring points inside the right and the left half-bucket, two 3D templates were made of glued paper. Each template has 152 perforations forming a grid with ±40 mm spacing. During the numerous measurements on the hard-coated surface over the years, the probe tips were eroded. This erosion was compensated in the data evaluation based on repeated reference measurements on uncoated spots. From the measurements before and after the sediment transport seasons, local and bucket-averaged differences of coating thickness were evaluated.

2.2.2 3D-surveys
The geometry of two buckets per runner was repeatedly measured using an optical digitizing system based on structured light projection and spatial triangulation (Comet L3D 5M from Steinbichler/Carl Zeiss Optotechnik, Germany). The projector and the camera are combined in one device, which is placed on a tripod in free positions, see Photo (a). The system has a resolution of 5 million points per shot. With a shot area of 480 mm by 400 mm, the average distance between points is 190 µm.

A whitening spray was applied to reduce glare. Small circular stickers were placed irregularly in- and outside the buckets. These stickers served as reference points to assemble the single shots to a numerical 3D-model (point cloud).

From these models, acquired before and after the sediment seasons, the increase of the splitter width in the central third of the splitter length, and the increase of the maximum cut-out depth were evaluated besides further geometrical differences. Moreover, the numerical 3D models enabled the extraction of cross-sections and to quantify eroded volumes.

2.3 Efficiency monitoring
The changes in turbine efficiencies Δη were determined with periodic sliding needle measurements and daily evaluation of operation data. The Δη-values are based on repeatedly determined index efficiencies. The term index efficiency means that no absolute efficiencies are measured.
2.3.1 Sliding needle measurements
Almquist et al. [199577] introduced the 'sliding gate method'. In this method, the guidevanes of a Kaplan turbine are continuously opened and closed while data are acquired for efficiency evaluation. This method has been adapted for Pelton turbines and is accordingly called the 'sliding needle method' [Abgottspon et al., 201310]. In a sliding needle index efficiency measurement, operation data are recorded in the SCADA system of the hydro plant, while the nozzles of a Pelton turbine are gradually opened and closed to operate the turbine from partial to full load and back to partial load (Fig. 5). At Fieschertal, the test duration is about one hour to achieve quasi-steady state conditions. Nevertheless, a sliding needle measurement takes less time than a series of classical index efficiency measurements at various load levels. Each sliding needle measurement yields a continuous curve of the turbine index efficiency as a function of power.

The procedure of the sliding needle measurement was programmed in the SCADA system. At each machine group (MG), up to six sliding needle measurements were conducted per year. Only one MG was running during such a measurement. Hence, the turbine discharge was obtained from the four-path ADM installation in the penstock.

From each efficiency curve, an average index efficiency for power outputs of between 16 and 31 MW was calculated with equal weighing factors. For each MG, absolute efficiency differences with respect to the first sliding needle measurement were evaluated.

2.3.2 Continuous efficiency monitoring
Operational data such as penstock discharge, needle positions and electric power outputs were continuously recorded at 1 Hz. The plausibility of single signals (such as pressure) was checked by comparing them with the values computed from physically related signals (head water level and discharge); such plausibility checks are elements of a so-called expert system.

The recorded signals were first smoothed (moving average) and then low-pass filtered. During steady state conditions, the index efficiency at a certain moment was computed for each turbine. Then an averaged difference of these index efficiencies of a certain day, compared with those from the last sliding needle measurement, was evaluated. After applying an outlier filter, a time series of daily \( \Delta \eta \) was obtained for each turbine.

3. Monitoring results
3.1 Suspended sediment
3.1.1 General particle properties
X-ray diffraction analysis of the dried residues of three water samples revealed the following mineralogical composition of the sediment particles (by mass):

- 25 to 40 per cent Quartz (Mohs hardness 7);
- 38 to 42 per cent Feldspars, Epidote and Hornblende (Mohs hardness 5.5 to 6.5); and,
- 21 to 37 per cent Mica and other sheet silicates (Mohs hardness \( \leq 3 \)).

On average, 76 per cent of the particles (by mass) are harder than the turbine steel (Mohs hardness 4.5). The solid density of the particle material was 2730 kg/m\(^3\) on average, which is plausible for this mineralogical composition. Microscope images showed that the particles are mainly angular and flaky (see Fig. 2a). Flaky particles are probably the soft ones (sheet silicates); the abrasive particles are mainly angular.

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Fig. 5. a) Measured suspended sediment concentrations (SSC) and loads (SSL) over three years and b) annual SSL by size classes [Felix et al. 20169].

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Considering a catchment area of 58 km², the average annual SSL corresponds to a surface erosion of 0.3 mm/year. According to Wittmann et al. [2007], the long-term denudation rate in the central Swiss Alps is 0.9 ± 0.3 mm/year. The difference is mainly attributed to the fact that less than the total sediment yield is transported through the penstock. Examples for this are suspended sediment in the river water not entering the intake and sediment returned to the river by flushing of the gravel trap, sand trap and the storage tunnel. Moreover, the three-year observation period with an exceptional event is too short to determine a reliable average SSL.

The SSL per turbine, calculated from the SSC measured in the penstock, are shown in Fig. 6a. Variations in annual SSL among the MGs are a result of differing annual average SSC and sediment loads. According to the LISST measurements, the median SSC was on average 11 µm (mainly silt). The SSC repeatedly reached several g/l. The highest SSC in these three years was 50 g/l in July 2012 (see Fig. 6a) during a flood event with a return period of ~20 years. From the SSC and discharge data, the annual suspended sediment loads (SSL) transported through the penstock were computed (see Fig. 6b). Assuming that 2012 was an exceptional year because of the flood event, the average annual SSL in the penstock was estimated as ~50 000 tons. In 2012, the SSL more than doubled (107 000 tons). The annual SSL varied mainly because of different annual average SSC and less as a result of the volumes of turbine water. During the flood event in 2012, 17 000 tons of fine sediment, corresponding to a third of the average annual SSL, passed the penstock in 39 h.

3.1.2 SSC and sediment loads
According to the continuous SSC measurements at the inlet of the penstock between 2012 and 2014, the average SSC was 0.5 g/l. During the summer (high flow season from mid-April to mid-October), the SSC repeatedly reached several g/l. The highest SSC in these three years was 50 g/l in July 2012 (see Fig. 6a) during a flood event with a return period of ~20 years. From the SSC and discharge data, the annual suspended sediment loads (SSL) transported through the penstock were computed (see Fig. 6b). Assuming that 2012 was an exceptional year because of the flood event, the average annual SSL in the penstock was estimated as ~50 000 tons. In 2012, the SSL more than doubled (107 000 tons). The annual SSL varied mainly because of different annual average SSC and less as a result of the volumes of turbine water. During the flood event in 2012, 17 000 tons of fine sediment, corresponding to a third of the average annual SSL, passed the penstock in 39 h.

3.1.3 PSD and fraction-wise sediment loads
According to the LISST measurements, the median particle size d50 was on average 11 µm (mainly medium silt). The d50 varied quite independently of SSC between 10 to 100 µm (medium silt to fine sand). Coarser particles were occasionally transported into the penstock when the water level in the storage tunnel (see Fig. 1) was low and the plant was operated at full load. In these conditions, coarser particles, which had settled previously, were re-suspended from the tunnel invert. In 2012, the percentage of coarser particles was higher than in the other years (see Fig. 6b). Because coarser particles have higher erosion rates, the erosion potential in 2012 was particularly high.

3.2 Turbine erosion
3.2.1 Coating erosion
In coated Pelton buckets, the erosion of coating on the splitter crests and at the cut-out edges (see Fig. 2b) is of major concern, because the softer base material is subsequently eroded, which leads to higher material loss and secondary damages. In these zones, the coating materials, such as hard coatings, have a higher erosion rate at such large angles (~60° to 90°). Brittle materials, such as hard coatings, have a higher erosion rate at such large angles (impact wear) than at low angles (sliding wear). The coating thickness measurements indicated that the erosion depth of the coating inside the bucket was reduced by up to 6.5 mm while the cut-out depth ∆h was increased by up to 8 mm. The eroded masses per bucket were 1.6 kg at the splitter crests and 1.5 kg at the cut-out edges. The runner of MG 2 had to be replaced before the scheduled maintenance in winter, leading to a downtime of 17 h during the runner change in summer (with production loss of 0.5 GWh).

3.2.2 Base material erosion
The highest base material erosion was measured on the runner of MG 2 from April to August 2012. Both turbines were running during the major flood event in July 2012. But, in contrast to MG 1, the runner of MG 2 was not in an as-new condition before the sediment season. The height difference Δh (yellow fill) is plotted in the upper part of Fig. 7a. Similarly, the erosion on the cut-outs is shown in Fig. 7b in the top view. The splitter height was reduced by up to 6.5 mm while the cut-out depth ∆c increased by up to 8 mm. The eroded masses per bucket were 1.6 kg at the splitter crests and 1.5 kg at the cut-out edges. The runner of MG 2 had to be replaced before the scheduled maintenance in winter, leading to a downtime of 17 h during the runner change in summer (with production loss of 0.5 GWh).
The splitter width is easily measurable with a ruler if the splitter crest is flatly eroded (as shown by the black line in Fig. 7d). The definition in Fig. 7d according to Abgottson et al. [2013] was introduced to determine the splitter width for rounded splitters as well, as being typical after grinding (initial crest shapes in Figs. 7c and 7d). This definition is also applicable to asymmetrically eroded splitter crests.

Fig. 8b shows the splitter widths of the runners in both turbines over the years. In 2013 for MG 1 and in 2014 for both MGs, the splitter widths remained unchanged because there was no systematic erosion of base material. In winters (low flow seasons), the blunt splitter crests and the irregularly eroded cut-out edges were rounded by grinding (Figure 8b) and the coating in these zones was repaired directly in the turbine housing (C in Fig. 8b).

### 3.3 Turbine efficiency

The series of the efficiency differences \( \Delta \eta \) obtained from the sliding needle measurements between 2012 and 2014 are shown in Fig. 8c for both turbines. The \( \Delta \eta \)-values refer to the first available measurements at the beginning of July 2012. Significant \( \Delta \eta \) (above the measurement uncertainty of about 0.2 per cent) were measured after the splitter crests and cut-out edges were eroded in the range of millimetres as a consequence of the loss of coating in these zones.

From July to the end of 2012, the turbine efficiency of MG 1 dropped by ~1 per cent. After grinding in winter, the efficiency improved by ~0.5 per cent. During the following winter, the beneficial effect of grinding on the efficiency was smaller because there was less additional erosion in 2013 than in 2012. Overall, the efficiencies decrease over the years and can only be recovered by factory refurbishment of the runners, such as welding and machining to restore the planned geometry.

### 4. Evaluation of monitoring results

#### 4.1 Turbine erosion as a function of the sediment load

Fig. 9 shows the increase in splitter width \( \Delta s \) (from Fig. 8b) as a function of the suspended sediment loads SSL per runner (from Fig. 8a) in the corresponding sediment seasons. The highest \( \Delta s \) of 3 mm corresponds to 0.5 per cent of the inner bucket width (vertical axis on the right of Fig. 9).

For SSL of ~25 000 tons per runner between the refurbishment works, the runners remained coated except for a few small spots or short grooves on the splitters, and the splitter width remained unchanged. However, for higher SSL, the coating was systematically eroded on the splitter crests and cut-out edges, followed by erosion of the softer base material. Above the threshold of ~25 000 tons, the splitter width increased on average 1 mm per 10 000 tons of SSL.

These results are valid for the specific conditions at the Fieschertal plant only. The following erosion model was applied so that the results are transferable to other hydro plants.

### 4.2 Adaptation and calibration of the IEC erosion model

The analytical erosion model described in IEC 62364 [2013] was adapted for coated Pelton buckets and calibrated based on the acquired field data. An important parameter in this model is the so-called particle load \( PL \) per bucket at the Fieschertal scheme.

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\[
P_L(t) = \frac{z_0}{z_1} \sum_{i=1}^{n} \frac{SSC_i}{k_{\text{size}} \cdot k_{\text{shape}} \cdot k_{\text{hardness}} \cdot \Delta t}
\]

where:
- \( z_0 \) = number of nozzles [-], 2 in the present case;
- \( z_2 \) = number of buckets [-], 20 in the present case;
- \( SSC \) = suspended sediment concentration [g/l], 0 if turbine is not running, otherwise variable in the present case;
- \( k_{\text{size}} \) = coefficient for particle size [-] = \( d_{50}/1000 \mu m \) according to IEC 62364 [2013], variable in the present case;
- \( k_{\text{shape}} \) = coefficient for particle shape [-] = 1 or 2 for rounded or angular, respectively, according to IEC 62364 [2013], assumed to be constant, 2 in the present case;
- \( k_{\text{hardness}} \) = coefficient for particle hardness [-] = mass fraction of particles harder than turbine steel, > 4.5 Mohs; assumed to be constant, 0.76 in the present case;
- \( \Delta t \) = time step duration [h], 600 h in the present case;
- \( i \) = time step number [-];
- \( t \) = end time of the considered period [h]; and,
- \( t_0 \) = start time of the considered period [h].

The \( P_L \) has units of mass concentration multiplied by time [g/l · h]. With more buckets \( z_2 \), the erosion per bucket is reduced. On the contrary, the erosion is increased if several jets \( z_0 \) act on a runner. The ratio \( z_0 / z_2 \) has already been described in Sulzer 1996 (partly published in DWA [2006]). For Fieschertal, the \( P_L \) is almost proportional to SSL because the plant is usually operated at full load during the sediment season. Therefore, it was possible to indicate the \( P_L \) on the horizontal axis at the top of Fig. 9.

To estimate the increase of splitter width \( \Delta s \) of coated Pelton runners, Eq. (2) is proposed:

\[
\Delta s(t) = C \cdot w \cdot (P_L(t) - P_{L0})
\]

where:
- \( C \) = calibration coefficient, corresponding to \( K_f \cdot K_m / R S^w \) in IEC 62364 [2013], summarizes the coefficients for the effects of the flow field \( K_f \), the resistance of the turbine material \( K_m \), and the turbine's reference size \( R S \) with its exponent \( p \);
- \( w \) = characteristic relative velocity between the flow and the turbine part, for Pelton buckets \( w = 0.5 \sqrt{2gh} \),
- \( \Delta s \) = increase of splitter width [mm],
- \( P_L(t) \) = particle load per bucket in the Fieschertal scheme.

\[C = \frac{K_f \cdot K_m}{R S^w} \]

Modified from [Felix 2017].
are the splitter widths \( s \) from Fig. 8b divided by the inner bucket width \( (B = 650 \text{ mm}) \). The lines for both MGs in Fig. 10 have a similar slope; the vertical offset is not relevant because the initial efficiencies were not the same. Moreover, the data of several runners from the Dorferbach hydro plant are shown in grey for comparison [Maldet 2008] (more recent data courtesy of TIWAG). Those runners have an inner bucket width of \( B = 228 \text{ mm} \) (smaller than at Fieschertal). Despite the different absolute splitter widths, the normalized data show similar initial relative splitter widths and a similar trend of efficiency depletion, comparable with the statement of Brekke et al. [2002].

### 5. Optimization of operation

#### 5.1 Estimation of shutdown SSC

The sediment monitoring showed that the SSC in the penstock varies considerably over time. Hence, the actual costs induced by hydro-abrasive erosion are also highly variable over time. When these costs exceed the revenues from power sales, it is economical to close the intake and to pause turbine operation. Of course, such operational optimization depends on higher-level boundary conditions such as production obligations and the possibilities to compensate the outage of a specific plant.

For Fieschertal, the average costs induced by the fine sediment were estimated at \( € 300,000 \text{/year} \) (Table 2). These costs are economically relevant because they correspond to 3.7 per cent of the nominal annual income of the plant, assuming an electricity wholesale price of \( € 0.05 \text{/kWh} \). For simplicity, it was assumed that the costs and production losses are proportional to the sediment load (~ 50,000 tons/year). Hence, it was estimated that each ton of fine sediment passing the turbines costs \( € 6 \).

At the average SSC of 0.5 g/l, the specific sediment-induced costs are thus \( € 0.003/m^3 \) of turbine water or \( € 0.0025/kWh \). If the SSC rises, for example, to 10 g/l (by a factor of 20), the sediment-induced costs are 0.05 €/kWh, which corresponds to the assumed wholesale electricity price. Hence, the 10 g/l are the so-called ‘shutdown SSC’, above which the electricity generation is unprofitable for the hydro plant studied. In the literature, shutdown SSCs between 1.1 and 10 g/l are reported [Boes, 2010; Singh et al., 2013; Espinoza, 2016]. The values of the shutdown SSC are site-specific, because they depend on the hydro plant’s head, the sediment properties as well as the type and characteristics of the turbines.

#### 5.2 Shutdown and restart procedure

A temporary shutdown and restart of a hydro plant requires some effort, and false alarms as a result of very short sediment peaks (the effect of a flushing procedure or measuring errors) should be avoided. Therefore it was proposed to shut down the Fieschertal plant if the SSC exceeds 10 g/l for at least 15 minutes and to resume operation if SSC will have fallen below 5 g/l. Since the flood in 2012, which occurred shortly after the beginning of the research project, the data to estimate the shutdown SSC have been compiled, the system for real-time suspended sediment monitoring and alarms has been improved and the organizational procedures have been adapted accordingly.
5.3 Shutdown scenario for a past flood event

With the rules proposed in the previous section, the hydropower plant would have been shut down for 16 hours during the major flood event in 2012 (see Fig. 11). In this scenario, 13,000 tons of fine sediment would not have passed the turbines during the 16 hours and, furthermore, 7,000 tons would not have entered the storage tunnel if the intake had been closed. Hence the SSL in the penstock could have been reduced by ~20,000 tons, which corresponds to about 40% of the SSL of a year without a major flood. The benefits of less hydro-erosive erosion and avoided consequential costs were roughly estimated as €260,000 (see Table 3). However, about 1 GWh would not have been generated, corresponding to a loss of around €50,000.

Considering some depreciation of the sediment monitoring system, a net benefit of around €200,000 would have resulted from the shutdown during the major flood event in 2012. This corresponds to almost 3% of the value of the annually generated electricity.

6. Conclusions

In this study on turbine erosion, the sediment load, the erosion on two hard-coated Pelton runners, and the turbine efficiency changes were measured and evaluated over several years in the high-head run-of-river Fieschertal hydropower plant, downstream of a major glacier in the Swiss Alps. In parallel, relevant monitoring techniques were investigated and further developed. To the knowledge of the authors, the selected combination of various methods for sediment monitoring and the comprehensive monitoring programme were an innovation.

The measurements showed a high variability of the suspended sediment loads over hours and from year to year. In 2012 with a major flood event, a rather worn-out runner was heavily eroded and had to be replaced before the scheduled maintenance in winter. This shows that erosion depends not only on the sediment load, but also on the condition of the runners before the exposure period.

Efficiency reductions as a result of hydro-erosive erosion of up to 1% per cent were measured. As a result of on-site refurbishment, such as the grinding of splitters and cut-out edges, efficiencies increased by up to 0.5% per cent.

The analytical erosion model described in IEC 62364 [2013], was adapted for coated Pelton buckets and calibrated based on the field data. Threshold values of suspended sediment and particle loads characterizing the start of systematic base material erosion were introduced and quantified. Below this threshold, mainly the coating is eroded on the splitters and cut-out edges. These zones were repaired on-site with limited effort (grinding and re-coating) between the sediment seasons.

Based on the measurement results and economic considerations, it was demonstrated that it is profitable to shut down a hydro plant in periods of high erosion potential. For example, in the major flood event of July 2012, a benefit corresponding to almost 3% of the value of the annually generated electricity would have resulted, if the intake of the plant had been closed and the turbine operation had been paused when the SSC exceeded 10 g/l.

Real-time sediment monitoring is an indispensable basis for short-term decision making in the operation of hydro plants at sediment-laden rivers. In addition, reliable and systematic monitoring of turbine erosion and efficiency, together with complete records on maintenance works and related costs, allow for optimizing the operation of hydropower plants with regard to profitability and electricity generation.

7. Outlook

The research project at Fieschertal will be continued. Additional instruments for sediment monitoring will be installed in the intake area to detect high SSC earlier and more reliably. The results obtained from the measurements in the first three years described here will be updated. A data set covering the sediment load, the turbine erosion and the efficiency changes of two turbines over several years is valuable for a better understanding of the effects of varying sediment loads and various refurbishment works. It is recommended to collect and evaluate similar data at other hydro plants to extend the database, calibrate and validate modelling approaches, and reduce their uncertainties. In parallel, it is recommended to investigate further the effects of particle size on the erosion rate in laboratory tests for uncoated and coated turbine parts under controlled conditions. With improved knowledge, shutdown criteria should be updated to consider particle sizes as well.

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