A FIELD STUDY OF HYDRO-ABRASIVE EROSION
IN THE SWISS ALPS

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ABSTRACT

Suspended sediments can cause severe damages to hydraulic machinery and other components of hydropower plants (HPP). In order to increase knowledge in the field a research study was carried out in the HPP Fieschertal, a plant in the Swiss Alps without storage reservoir and equipped with Pelton turbines. Suspended sediment mass concentration (SSC) and particle size distribution (PSD) were measured. Continuous measurements were performed using a laser diffractometer, a series of different turbidimeters and in addition also the signal attenuation of the acoustic signals in an existing flow meter was measured. Reference samples were analyzed in the laboratory.

The results show that not only SSC but also PSD may vary considerably in time. In an example period of ten summer days, SSC ranged between 0.2 and approx. 10 g/l, the median particle size $d_{50}$ increased occasionally from 12 to approximately 100 $\mu$m.

For Pelton turbines, the efficiency decrease caused by hydro-abrasive erosion is mainly due to geometrical changes in the bucket profile. To quantify these effects efficiency was determined in regular intervals and erosion was measured with a 3D scanner. Erosion rates determined over one sediment season at the HPP Fieschertal were in the range of 4 to 5 mm for the main splitter height, 2 to 3 mm for the main splitter width and 7 to 9 mm for the cut-out section. A decrease in efficiency of 0.9 percent for a little more than half the sediment season was observed in 2012 at one runner. Due to maintenance works on that runner during the winter the efficiency increased afterwards by 0.5 percent. The index efficiency was evaluated based on each of the different discharge measurement instruments installed at HPP Fieschertal. The results with acoustic discharge measurement indicate the best reproducibility being within 0.2 percent.

1. INTRODUCTION

The Alps as well the Himalayas are of the same tectonic age and both regions are exposed to a retreat of glaciers. This and the young age of both mountain ranges lead to pronounced soil erosion. For hydro power plants (HPPs) sediments might become detrimental for all mechanical equipment exposed to sediment-laden flow. Especially all elements where high relative flow velocities and curvature of streamlines occur encounter hydro-abrasive erosion. For HPPs with small reservoirs a sediment management becomes essential. The recently published standard IEC 62364 [1] describes the state of the art of the knowledge concerning hydro-abrasive erosion in Kaplan, Francis and Pelton turbines. Erosion is greatly dependent on the particle velocity, e.g. IEC mentions an exponent of $n=3.4$. Further influencing parameters
are the particle concentration, the physical properties of the particles, the local flow and the impingement angle, the degree of turbulence, and the particle diameter and shape. On the other hand the resistance to erosion depends on the material or the coating of turbine components. It is not fully understood to what extent all these parameters contribute to the damaging mechanisms.

Concerning local flow phenomena one has to be aware that local acceleration or deceleration leads to different forces on particles and the surrounding fluid and thus to a relative motion of particles to the fluid flow. Acceleration or deceleration arises from velocity changes in the turbine components, curvature of streamlines, centrifugal and Coriolis accelerations. The relative motion due to all of these accelerations leads to particle paths being different from that of the fluid. Accelerations or decelerations can reach very high values, e.g. for Pelton turbines $10-50 \times 10^3 \text{ m/s}^2$. The relative motion of the particles may lead eventually to turbulent relative flow around the particles potentially enhancing erosion.

Real-time measurement of particle concentrations and size distributions in HPPs poses a challenge for various reasons. In order to gain experience with different measuring methods the case study at HPP Fieschertal was carried out. The overall goal of this project initiated by the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at the Swiss Federal Institute of Technology Zurich and the Hochschule Luzern in Switzerland, was to advance the understanding of the interactions between suspended sediment load, turbine wear and efficiency. This knowledge will serve as a basis for optimization of the machine operation and maintenance management.

Fieschertal is a run-of-river scheme in the Swiss Alps, with a net head of 509 m. Since the plant began operating in 1976, severe hydro-abrasive erosion has been observed at the needles, nozzles and runners of the two 32 MW Pelton units. Coating of turbines and other hydraulic parts reduced the extent of damage, but sediment handling and optimized operation and maintenance of the plant remain important economic issues, since hydro-abrasive erosion on turbines may lead to maintenance and repair costs as well as significant generation losses due to reduced turbine efficiency or downtimes.

For Pelton turbines, the efficiency decrease caused by hydro-abrasive erosion is mainly due to geometrical changes in the bucket profile. These geometrical changes due to primary erosion or secondary cavitation erosion can be local or extended damages over the entire bucket surface. The location of such damages is influenced by the local flow field, which itself is affected by progressive wear. 3D digitization of selected Pelton buckets with a scanner allowed quantifying material losses at relevant parts like the main splitter and the cut-out section. In the HPP Fieschertal different methods to quantify such material losses were tested, e.g. reduction of height, increase of width and volume differences at the main splitter, and geometrical changes at the cut-outs. Changes in efficiency were evaluated based on periodical measurements with the sliding needle index measurement method.
2. METHODS FOR MEASUREMENT OF SEDIMENT LOADS

The potential for hydro-abrasive erosion of a particle load can be characterized by:

- Suspended sediment (mass) concentration (SSC),
- Particles size distribution (PSD),
- Hardness (mineralogical composition) and shape of the mineral particles.

The following optical and acoustic devices were employed for continuous measurements in the HPP Fieschertal:

- Turbidimeters,
- Portable laser diffractometer,
- Attenuation measurement of the acoustic pulses of the installed acoustic flow meter.

Turbidity meters, or in short turbidimeters, measure the attenuation and/or scattering of near infrared or laser light. The readings of the turbidimeters (displayed in optical units) have to be calibrated in order to get a measure for the SSC. PSD cannot be determined from turbidimeters.

The Laser diffractometer (LD) provides information on SSC as well as on PSD. For the use in HPPs specific models of LD devices were developed by Agrawal et al. [2]. In order to extend the range of measurable SSC the optical path length of the LD was reduced from 50 mm to 5 mm by insertion of a glass cylinder (90 percent path reduction module). The used LD has a nominal particle size measuring range from 2 to 380 μm.

For the reference measurements samples were taken every three days, or more frequent, triggered by the turbidimeters, in case of events with high sediments loads. From each bottle sample the SSC was determined in the laboratory by weighing before and after drying in an oven.

From selected samples the quantitative mineralogical composition was determined using x-ray diffraction. The samples contain mainly quartz, feldspar and mica, i.e. the main components of granite rock. The solid density of selected samples of mineral particles was determined by means of a gas pycnometer and was found to be close to the density of quartz (2.65 g/cm³).
Fig. 1: Schematic of the HPP Fieschertal and of the taken measurements [3], [6]

Details of the measuring techniques employed in the HPP Fieschertal are described by Felix et al. [3].

At the time of the project a most promising new technique based on acoustic multi-frequency backscatter measurements, as described by Hies et al. [4] was not yet available.

3. TIME SERIES OF SUSPENDED SEDIMENT CONCENTRATION AND PARTICLE SIZE

From the time series of SSC and median particle size $d_{50}$ obtained from LD, an extract of ten days during the sediment season in 2012 is presented in Fig. 2. The median particle size $d_{50}$ stands for the diameter of graded particles of which 50 percent by mass are smaller. Whereas the average SSC during this period was 0.5 g/l, periods of increased SSC ranging up to several g/l for some hours occurred (Fig. 2b). Strong SSC increases occur within less than a few hours, decreases however are generally slower. Calibrated SSC is in overall good agreement with reference SSCs (circular markers in Fig. 2b).

The median particle size $d_{50}$ had a base level of 12 μm and rose occasionally up to approx. 100 μm (Fig 2a). Periods of increased SSC are mostly associated with the occurrence of coarser particles. The time series of SSC and $d_{50}$ are, however, not synchronous and time shifts among peaks in SSC and $d_{50}$ were observed.
Fig. 3 shows a detail with one selected period of increased SSC (suspended sediment transport event), as indicated by the shaded areas in Fig. 2. SSC obtained from LD rose from 0.2 g/l to several g/l and fell back to 0.4 g/l (Fig. 3b). The SSC-estimate from LD is supported by one bottle sample. With the particle sizes in this event, LD measurements were possible until approx. 10 g/l and resumed when SSC was falling below approx. 7 g/l.

In Fig. 3a, \( d_{16} \) and \( d_{84} \), i.e. the sizes of particles of which 16 or 84 percent by mass are smaller, are plotted in addition to \( d_{50} \). The diameters \( d_{16} \) and \( d_{84} \) are often used in geotechnical and river engineering to characterize the “width”, i.e. the so called spreading, of a PSD. \( d_{84} \) of up to approx. 200 \( \mu m \) was measured, this is smaller than the classical design grain size for sand traps of 250 to 300 \( \mu m \). Whereas SSC decayed rather continually after the peak, \( d_{50} \) remained at an elevated level until SSC fell back to the base level.

In addition to LD, SSC estimates from the other SSM devices in the valve chamber are displayed in Fig. 3b. The turbidimeter signals were de-trended in order to compensate signal drift caused by accumulating contamination of the optical windows in the flow-cells. It turned out that the flow in the flow-cells is not strong enough for self-cleaning and that occasional flushing of the sampling pipe without manual cleaning of the windows in the flow-cells was insufficient to prevent signal drift.

\[ 0 \quad 50 \quad 100 \quad 150 \]

\[ \text{day in 2012} \]

\[ 222 \quad 223 \quad 224 \quad 225 \quad 226 \quad 227 \quad 228 \quad 229 \quad 230 \quad 231 \quad 232 \]

\[ \text{SSC (g/l)} \]

\[ \text{Detail see Figure 5} \]

**Fig. 2**: Time series of (a) \( d_{50} \) and (b) SSC in the turbine water obtained from LD after calibration to reference SSCs from bottled samples (circular markers); example of ten days in summer (from Aug. 10 to 19, 2012) [3]
In order to compare the geometries of Pelton buckets measured in a series of turbine inspections, a consistent and reproducible geometrical reference had to be used for the positioning of the digital geometric models (3D point clouds) of the buckets. The surfaces A, B1, B2 and the outer radius ra in Fig. 4 were not affected by abrasion or by maintenance works at the runners. Based on these surfaces, a local Cartesian coordinate system was defined in the bucket. The coordinate system was placed using surface A as xy-plane. Surface B,
which is the mid-plane of B1 and B2, sets the origin of the x-coordinate. The origin of the y-coordinate was set to the intersection of plane B with the outer radius ra (plane C).

Fig. 4: Digitized Pelton buckets and definition of the coordinate system [6]

One way to analyze the abrasion at the main splitter is to evaluate its height. The measured splitter profile was compared to a straight reference top line of the splitter (red line in Fig. 5). The angle and position of the reference splitter top line can be taken from construction drawings of the runner or from a measurement at a new runner. The distance from the actual splitter profile perpendicular to the reference splitter top line is defined as h (Fig. 5). The eroded splitter height h is evaluated along the splitter, not including the region of the splitter tip and the area of the transition to the bucket root. The boundaries, between the eroded splitter height was evaluated, are shown in Fig. 5 and were used in all analysis related to the main splitter.

Fig. 5: Definition of eroded splitter height of a Pelton bucket [6]

Another way to monitor turbine wear is to measure the width of the main splitter. An increase of splitter width is known to be associated with an efficiency decrease. The splitter width can be considered to be one the key parameter describing the effect of hydro-abrasive erosion at a Pelton bucket. If a coated splitter is eroded the splitter width is clearly visible because of its flat top surface and sharp edges to its flanks. In case of a splitter top with rounded cross section, however, the definition of splitter width is not evident, partly because the gradients of the splitter flanks vary along the splitter length.

Therefore, the splitter width was determined in cross sections of the splitter (normal to the y-axis). Fig. 6 shows two examples of such cross sections in the region of the top of the splitter, one before and one after the sediment season. The dots represent the splitter geometries; the
lines indicate the respective gradients from point to point. The splitter width \( w \) was defined as the distance (in x-direction) between points on both flanks of the splitter where the slope is 2:1 (\( z:x \)), see Fig. 6. The plotted gradients were set to zero if the gradient was steeper than this limit.

Fig. 6: Definition of the main splitter width of a Pelton bucket [6]

The erosion at the cut-out section is determined as difference in the cut-out depths. The cut-out depth \( d \) is measured in top view of a bucket from the outer radius of the runner (origin of local coordinate system) to the cut-out contour projected into the xy-plane (Fig. 7). The cut-out depth was evaluated in cutting planes normal to the x-axis at increments of 1 mm. Extracting the smallest y-values with their corresponding x-value yields the cut-out depths from left to right. This method is simple and well reproducible. No interpolation is needed to calculate the differences in cut-out depths because the same locations of the cross sections can be used.

6. INSPECTION DATES AND DESCRIPTION OF RUNNER CONDITIONS

In the HPP Fieschertal two machine groups (1 and 2) with one Pelton runner each are installed. Turbine wear was determined at two buckets of each runner. Altogether four buckets were analyzed by a comparison of measurements before and after the sediment season (see Table 1).

At HPP Fieschertal the sediment season, i.e. the period with increased suspended sediment concentration, is approximately between Mai and October. 50 percent of annual turbine discharge and power generation are normally in July and August, only 5 percent from November to April. On July 2 and 3, 2012, a major thunderstorm occurred in the region, which produced a flood discharge with an estimated return period between 10 and 30 years (Felix et al. [3]). The turbines were running at suspended sediment concentration of up to approx. 50 g/l. After this event the runner in machine group 2 had to be replaced due to heavy damages. In the following, the second measurement of turbine geometry at this runner is also called “after sediment season”, even though this runner was not in operation during the full
sediment season. The runner in machine group 1, however, exhibited less damages after the flood event and could be operated until the end of the season, when it was revised on site.

![Fig. 7: Definition of the cut-out depth at a Pelton bucket [6]](image)

Table 1: Dates of turbine geometry measurements and respective runner conditions at HPP Fieschertal [6]

<table>
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<tr>
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<th>machine group 2</th>
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<tr>
<td>date of first measurement</td>
<td>Mai 2012 before sediment season</td>
<td>April 2012 before sediment season</td>
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<tr>
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<td>3</td>
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<td>operation since last factory</td>
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<td>after annual on-site revision (grinding and local</td>
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<td>overhaul</td>
<td>coating</td>
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<td>“heavy wear”</td>
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<tr>
<td>date of second measurement</td>
<td>February 2013 after sediment season / before next</td>
<td>August 2012 during sediment season, taken out of</td>
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<td>operation</td>
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<tr>
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7. RESULTS OF PELTON TURBINE WEAR MEASUREMENTS

Results of the bucket geometry measurements are given for the parameters as defined above \((h, w and d)\). The following plots include geometrical quantities measured before and after the sediment season as well as the calculated differences \((\Delta h, \Delta w and \Delta d)\). In addition, the volume differences, i.e. mass losses, were calculated at main splitters to give an example of further possibilities of the described method using digitized geometries.
Fig. 8 shows the shapes of the four examined main splitters before and after the sediment season. Comparing the machine groups, an important difference in the initial conditions can be seen. With a similar splitter height reduction on both machines (see Fig. 9) the volume differences at machine group 2 were considerably greater since the width of the splitter increased with erosion. The average material loss observed at machine group 2 is almost twice that of machine group 1, what is attributed to the different initial conditions. The volume differences for the buckets 1 and 2 of the machine group 2 are very similar, but for the buckets of the machine group 1 they vary significantly.

During the sediment season 2012 a splitter width increase of in maximum 3 mm for machine group 1 and 2 mm for machine group 2 were evaluated (Fig. 10). This is 0.3 to 0.5 percent of the inner bucket width. Similarly to the difference in splitter height, the difference in splitter width has its maximum approximately at half of the splitter length, where the splitter was hit most frequently by the jet of sediment-laden water.

During the sediment season 2012 the splitter height was reduced by about 4 mm for the machine group 1 and by 5 mm for the machine group 2 in the central part of the splitter length (Fig. 9). This corresponds to 0.6 to 0.8 percent of the Pelton bucket inner width of 650 mm at HPP Fieschertal. Dimensionless quantifications are used e.g. for correlating relative splitter width increase and efficiency decrease at different HPP with various bucket sizes. As mentioned before, the top of the splitters at machine group 1 was almost straight before the sediment season (red line).

Further damages occurred at the cut-out section of the Pelton buckets. The top views of bucket no. 1 are shown in Fig. 11 for both machine groups. The shape of the cut-outs differs considerably between both units (compare the green and red lines in Fig. 11). The shape of cut-outs is influenced by the different number and the extent of revisions (grinding and
welding) performed at the runners. The increase in cut-out depth $\Delta d$ varies between the two machine groups. Cut-out depths increased by up to 10 mm towards the turbine axis at machine group 1 and by up to 7 mm at machine group 2. This corresponds to 1.0 to 1.5 percent of the inner bucket width.

Fig. 9: Side view of the main splitter for machine group 1 (upper) and 2 (lower): Red and green lines show splitter profiles before and after the sediment season for bucket 1, black lines indicate the differences (erosion heights $\Delta h$) for buckets 1 and 2 [6]

Fig. 10: Splitter widths along the main splitter for machine group 1 (upper) and 2 (lower): Red and green lines in the lower parts of the diagrams show splitter widths before and after the sediment season for bucket 1, black lines indicate the differences ($\Delta w$) for buckets 1 and 2 [6]
8. INDEX EFFICIENCY MEASUREMENTS

Turbine efficiency history at HPP Fieschertal is measured using the periodical sliding needle index measurement method (Abgottspon et al. [7]). “Sliding needle” stands for a gradual variation of turbine discharge between part load and full load during the measurement in case of Pelton turbines. Measurements involve the recording of electric power output, pressure upstream of the turbine and turbine discharge during a test, which takes slightly more than an hour for one machine group. For the determination of turbine discharge, acoustic discharge measurement installations at the top and the bottom of the penstock and two differential pressure sensors at a Venturi pipe section upstream of each machine group are available at HPP Fieschertal. The term “index efficiency” stands for the fact that no absolute efficiencies are measured. Measurements with this method are less laborious and less expensive than measuring absolute efficiency. The results allow establishing a history of efficiency changes, what is suitable for the present application.

In Fig. 12 the efficiency histories of both machine groups are plotted since the sliding needle measurement program was implemented in the control system of the HPP Fieschertal. Plotted index efficiencies are a weighted average (according to the average load profile) of the index efficiencies determined between 40 and 100 percent of installed power. At machine group 2 no measurements were possible for some months because one needle servomotor was not fully operational. Both histories begin with a reference index efficiency of 0 percent. No absolute efficiency differences among both units can be analyzed from the diagrams below.

Furthermore, information on revision works at the Pelton buckets and qualitative information on sediment load is given for the respective periods. According to IEC Standard 62364 [1] particle load is defined as the integral of the product of suspended sediment concentration and weighting factors for particle size, shape and hardness over time.
The index efficiency decrease of 0.9 percent for machine group 1 is attributed to hydro-abrasive erosion. A major sediment transport event occurred in Fieschertal on July 2 and 3, 2012. This was prior to the first index efficiency measurement on July 4, 2012. It is assumed that a considerable efficiency decrease has occurred in the first half of the sediment season 2012 including the flood event.

The observed index efficiency increase of 0.5 percent at machine group 1 can be explained with grinding works carried out at the main splitters and cut-out sections of the Pelton buckets during winter.

9. CONCLUSION AND OUTLOOK

The suitability of a portable lasers diffractometer and of a series of turbidimeter was tested for continuous monitoring of the suspended sediment load. Suspended sediment concentration (SSC) as well as particle size distributions (PSD) were determined over time. Also the measurements of the acoustic signal attenuation of the installed acoustic flowmeter provided, especially for high concentrations, a good measure for the SSC. All methods needed calibration from samples analyzed in the laboratory. Turbidimeters showed to be sensitive to a drift of the signals with time. SSC and PSD time series based on LD will be used in a next step to calculate the so called ‘particle load’ that was passing the turbines in time intervals between turbine inspections or efficiency measurements. According to IEC Standard 62364 [1], particle load is defined as the integral of the product of SSC and weighting factors for particle size, shape and hardness over time.

Turbine wear was investigated on two buckets of two Pelton runners. Based on digital geometrical models measured before and after the sediment season, changes in geometry of areas that are most exposed to hydro-abrasive erosion were evaluated. For the main splitter, the reduction in height, increase of width and lost material volume were defined and calculated, for the cut-outs the increase of cut-out depth in radial direction were examined. Whereas an approximate value of the main splitter width can be quickly obtained with a ruler at a turbine inspection, the changes in cut-out geometry, the current shape of the main
splitter’s longitudinal profile or material loss cannot be quantified “by hand” and visual inspection in such accuracy as with the described method based on digitizing. In particular, a method for the evaluation of actual main splitter width, based on the gradient of the splitter flanks, was proposed. Digitizing of at least two buckets per runner is advisable to get reasonable average values.

A series of index efficiency measurements was performed by the sliding needle method. Among other parameters, the signals of four independent devices for the determination of turbine discharge were recorded. The evaluation of these measurements showed best results using acoustic discharge measurements. Besides efficiency reduction due to hydro-abrasive erosion, an increase of efficiency due to maintenance works (grinding of splitter and cut-out edges) was measured. The method is suitable for the determination of an index efficiency history since the reproducibility is 0.2 percent and relevant changes in efficiency over the sediment season or due to maintenance works in winter can be quantified.

It is planned in future studies to correlate the measurements of suspended sediment, turbine wear and turbine efficiency in order to contribute to the development of respective prediction formulas.

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REFERENCES