Monitoring Suspended Sediment and Turbine Efficiency

Sediment in the water passing through hydro turbines can have a significant effect on unit efficiency. The authors undertook a research project to better understand the interactions between suspended sediment, turbine wear and unit efficiency.

Abrasive particles in the water powering hydroelectric plants reduce unit efficiency, increase maintenance costs and may cause turbine downtime and associated production losses. To deal with this situation (called hydro-abrasive wear or hydro-abrasive erosion) during the design, operation and maintenance of hydro plants, knowledge of turbine wear needs to be improved and relevant parameters — i.e., suspended sediment concentration (SSC); size, hardness and shape of particles; relative velocity between the flow and turbine parts; turbine geometry and turbine material — need to be quantified. It is not fully understood to what extent these parameters contribute to the dominant damages. Monitoring SSC and particle size distribution (PSD) is still not common, and the effect of hydro-abrasive erosion on efficiency is only qualitatively known.

In a project initiated by the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at the Swiss Federal Institute of Technology Zurich and Hochschule Luzern in Switzerland, hydro-abrasive erosion has been investigated by means of a case study at the Fieschertal hydro plant. The goal is to advance in a better understanding of interactions between suspended sediment load, turbine wear and efficiency as a basis for economic and environmental optimization.

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 damages — i.e., suspended sediment concentration (SSC); size, hardness and shape of particles; relative velocity between the flow and turbine parts; turbine geometry and turbine material — need to be quantified as described in the literature. The so-called particle load is calculated from SSC, operating hours and weighting factors for particle size, shape and hardness.

SSC and PSD are continuously measured as they may vary considerably over time. Particle shape and hardness, however, are assumed to be constant properties of the catchment area. According to X-ray diffraction analysis, the sediments at the Fieschertal plant consist mainly of quartz and feldspar and about 20% mica. Quartz and feldspar with Mohs hardness of 6 to 7 are particularly abrasive, whereas Mica is not harmful to turbines. Microscope images reveal that the hard particles are very angular, which adds to their abrasion potential.

Among the techniques for suspended sediment monitoring (SSM), turbidimeters are most popular, despite the fact that their calibration is strongly particle-size dependent and needs generally to be established by the user. Various kinds of turbidimeters (measuring optical transmission or scattering) have been used in this study. An acoustic method for SSM based on installations for acoustic discharge measurement is also applied (single frequency attenuation). Furthermore, a portable laser diffractometer (LISST) is used to estimate SSC and PSD. Particle size is an important parameter in the context of turbine wear.

This article presents the results on suspended sediment, turbine wear and efficiency monitoring. SSC in the water passing through the turbines is monitored using optical and acoustic devices, such as turbidimeters, a laser diffractometer and a method based on acoustic signal attenuation. The inspections giving indications of wear are documented with photographs. Turbine wear is quantified by surface mapping using a three-dimensional optical scanner. The evolution of turbine efficiency is measured by periodic index tests.

Suspended sediment monitoring

The sediment load passing through the turbines can be quantified as described in the literature. The so-called particle load is calculated from SSC, operating hours and weighting factors for particle size, shape and hardness.
were tested in the hydraulic laboratory at Hochschule Luzern, Competence Centre for Fluid Mechanics and Hydro Machines. In summer 2012, they were installed at Fieschertal. Most devices are installed in the valve chamber, at the inlet to the penstock. Information on these devices, laboratory tests, installation at the plant, and previous results is available.2,7

An automatic water sampler was installed in the valve chamber and the samples are analyzed in the laboratory as a reference for the other devices. Reference SSCs are determined by weighing the solid residues. The sampler is programmed to take a sample every two days and is triggered by the signal of a turbidimeter to increase the sampling rate during relatively high SSC.

Figure 1 shows an example of suspended sediment transport during three summer days. In addition to SSCs determined by various methods, the figure also shows three of the reference SSCs from laboratory analysis of bottled samples and the time series of the median size of the particles in the turbine water (d50, i.e. the median diameter by mass) obtained from the LISST.

During the summer, SSC was about 0.5 g/l. The time series from all devices show similar behavior, except for a sediment transport peak early on Aug. 27. During this event, the LISST yields a higher SSC compared to the other measuring methods. The LISST measurement is supported by the reference measurement taken during the rising limb of the SSC peak. The median size of the particles in the turbine water is about 15 microns, except for the phase of increased sediment transport. During this phase, about three times coarser particles (d50 about 45 microns for some hours) were transported. The maximum d50 occurred about one hour after the maximum SSC was reached.

Figure 2 shows PSDs obtained from the LISST. The times at which these PSDs were measured are indicated in Figure 1. The PSDs measured before (B) and after (E) the SSC peak, as well as during a minor SSC peak (A), are similar. The PSDs recorded at maximum SSC (C) and at maximum d50 (D) are considerably coarser.

The underestimation of SSC by the turbidimeters and the acoustic method in the times with transport of coarser particles is related to their physical operating principles. Coarser particles do not cause as much turbidity or scattering as finer ones (at the same SSC). The calibration of those devices depends strongly on particle size, for which a constant value has to be adopted. As Figure 1 shows, the deviation in SSC estimates of those devices with respect to SSC from the LISST and reference SSCs may be significant during phases of increased suspended sediment transport.

**Turbine wear measurements**

Erosion of coated Pelton buckets is mainly observed at the splitter and the cut-out of the buckets. The widening of the splitter is of special importance: if the splitter width increases to 1% of the bucket width, efficiency drops by about the same amount at full load.8 The increase of splitter width has been related to suspended sediment load.8

The geometries of selected buckets of the runners at Fieschertal were measured using a 3D optical scanning camera inside the turbine casing. Because the stainless steel buckets reflect light, a whitening spray was applied prior to scanning. Reference
markers were used to improve the matching of point clouds and the measuring accuracy.

Figures 3 and 4 show the geometric changes due to hydro-abrasive erosion at splitters, obtained from comparisons of digital geometric models taken before and after the sediment season. At the beginning of sediment season 2012, the Unit 1 runner was fully reconditioned (welding, grinding and complete coating, with geometry close to planned geometry). The Unit 2 runner, however, has been in use for several seasons after the last factory overhaul and was repaired on site (grinding and local re-coating).

Figure 3 shows hydro-abrasive erosion at the splitter (analyzed as height differences along its longitudinal profile) for Bucket 1 of both runners. In summer 2012, a major flood event with SSC up to about 50 g/l occurred when both turbines were running. During sediment season 2012, splitter height was reduced by about 3 mm after 3,426 operating hours for Unit 1 and by 5 mm after 1,430 operating hours for Unit 2. These numbers indicate that hydro-abrasive erosion does not mainly depend on operating hours but rather on suspended sediment transport events (e.g. during floods) and on the geometry of the splitters at the beginning of the sediment season (see Figure 4).

The cut-outs were abraded by up to 9 mm toward the turbine axis in Unit 1 and by up to 6 mm in Unit 2.

**Efficiency monitoring**

Turbine wear reduces efficiency. Little published data is available\(^9\) describing quantitatively the efficiency decay, correlated to various types of minor turbine damages and long-term exposure to suspended sediment load. One main reason for this lack of data is the effort associated with efficiency measurements with respect to direct costs and cost of eventual power losses during efficiency measurements.

With index efficiency measurements, the efficiency changes between two tests can be determined; absolute efficiency data are not required. Classical index efficiency measurements encompass a series of measuring points (part load to full load) with constant operating conditions. Such measurements are time-consuming. In the “sliding gate” method, the guide vanes of a Kaplan turbine were continuously opened and closed while acquiring data for efficiency evaluation.\(^11\) This method has been adapted to Pelton and Francis turbines.\(^12\) The main advantages of this kind of index efficiency method are:

- Feasible for Kaplan, Francis and Pelton turbines;
- Reduced time required to perform efficiency tests; and
- Continuous efficiency curves over the entire operating range, instead of discrete points.

A further advantage is that in most cases the instrumentation of the hydro plant can be used or data can be extracted from the control system. To do so, an adequate data acquisition algorithm has to be implemented in the control system. At Fieschertal, three possibilities to calculate the index efficiency are available:

- Acoustic discharge measurements at the upper and lower ends of the pressure shaft;
- Pressure difference measurements in a Venturi pipe section upstream of each machine group; and
- Needle stroke measurements.

Figure 5 on page 34 shows the efficiency history of Unit 1, calculated twice (independently) based on the two available acoustic discharge measurements. The differences between the instruments indicate reproducibility within 0.2%.

Between the measurements of July 4, 2012, and Sept. 27, 2012, more than half of the sediment season passed. An index efficiency decrease of 0.9% was obtained, attributed to hydro-abrasive erosion. On Nov. 5, 2012, none or only a minor rise in...
The index efficiency decreased due to hydro-abrasive erosion and increased due to turbine maintenance. Index efficiencies were calculated twice, based on the two available discharge measurements. The index efficiency decreased due to hydro-abrasive erosion and increased due to turbine maintenance. Index efficiencies were calculated twice, based on the two available discharge measurements.

Conclusions

Using several devices for SSM based on different physical principles allows for a comparison of their measuring capabilities and leads to higher reliability. Combining devices for continuous SSM with an automatic water sampler allows calibrating the devices based on site-specific conditions with respect to typically prevailing particle sizes and mineralogical composition. The calibration of the devices will be improved based on the increasing data set of reference SSC from the study site.

For turbidimeters it is recommended to use the specific models with an automatic cleaning system (wiper or pressurized air) or with optics not in contact with the sediment-laden flow (free falling jet type). The acoustic method based on acoustic discharge measurement installations existing in many hydro plants offers the advantage of monitoring suspended sediment directly in the penstock. Among the devices used, LISST offers new possibilities for SSM because it provides information on both SSC and PSD. In environments with variable particle sizes, LISST measures SSC more accurately than devices with a fixed calibration depending on particle size. Measuring PSD is important because coarser particles have higher abrasion potential (for a given SSC) and are therefore particularly harmful to turbines. Devices with particle size-dependent calibration may be used as pragmatic contributions to a real-time decision making system for the operation and maintenance of hydro plants.

In summer 2012, SSC of about 0.5 g/l with d50 of normally 15 microns was observed in the turbine water of Fieschertal. The measurements confirmed that SSC and PSD may vary strongly within a short time, e.g., due to precipitation events. The wear at coated runner buckets was measured with a 3D optical scanner. Digital models of selected Pelton buckets allowed quantifying material losses at the main splitter and at the cut-outs due to turbine operation over a sediment season. The splitter height decreased 3 to 5 mm during the sediment season 2012, corresponding to about 0.5% to 0.8% of the inner bucket width. Hydro-abrasive erosion at the splitter was influenced by the splitter geometry at the beginning of the sediment season, particle load and the operating hours.

Turbine efficiency was periodically evaluated by “sliding needle” index measurements. The history of the index efficiency permits to identify relevant efficiency variations due to hydro-abrasive erosion. For one investigated turbine, the efficiency decrease was 0.9% for half of the sediment season 2012. To distinguish the effects of hydro-abrasive erosion and the effects of maintenance works at relevant turbine parts (e.g. grinding of the splitter) on efficiency, index tests should be performed before and after such works.

First analyses of the hydro-abrasive erosion rates for both units at Fieschertal showed that single events such as heavy rains lead to major material loss at Pelton buckets and significant efficiency drops. Plant shutdowns during such events would help to prevent excessive hydro-abrasive erosion.

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Notes


Reference