HYDRO-ABRASIVE EROSION OF PELTON BUCKETS AND SUSPENDED SEDIMENT MONITORING

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ABSTRACT

Wear of turbine parts due to abrasive particles in the water of hydroelectric power plants (HPP) is of special importance for Pelton turbines where extreme redirection and deceleration of the flow occurs. In an on-going research project at HPP Fieschertal, Switzerland, wear on coated runner buckets is measured with a 3D optical scanner and a thickness gauge, turbine efficiency is periodically evaluated by "sliding needle" index tests and suspended sediment is monitored using various devices.

3D digitizations (measurements) of selected Pelton buckets allow quantifying material losses of the main splitter or of the cut-out section due to turbine operation during a sediment season. In the sediment season 2012 the splitter height decreased in the range of 3 to 5 mm, i.e. approximately 0.5 to 0.8 percent of the inner bucket width of 650 mm. The erosion on the splitter is influenced by the initial geometric condition of the splitter, the particle load and the operating hours.

The history of the index efficiency permits to identify relevant efficiency variations due to hydro-abrasive erosion or due to mechanical works on the turbine runner (e.g. grinding of the splitters). Measurements before and after mechanical works and during the sediment season (with no mechanical works) allow to separate both effects. For one runner the efficiency decrease was 0.9 percent for more than the half sediment season 2012.

Turbidimeters, an acoustic method and a laser diffractometer (LISST) were site-specifically calibrated based on automatically taken water samples. The measurements confirm that suspended sediment concentration (SSC) and particle size distribution (PSD) in turbine water may vary strongly in time. The LISST provides not only SSC but also PSD which is important in the context of hydro-abrasive erosion. All devices yielded similar SSC at low to moderate levels while the LISST measured SSC more accurately during periods of increased SSC with transport of coarser particles. Accepting a temporary bias, turbidimeters and the acoustic method can be used as pragmatic contributions to a real-time decision making system for the operation and maintenance of HPPs.

1. INTRODUCTION

The complications associated with wear due to abrasive particles in the water of hydropower plants (HPPs), so called hydro-abrasive wear or hydro-abrasive erosion, are not new, but the issue is increasingly emphasized because of the worldwide growing energy demand. Hydro-abrasive erosion has a detrimental effect on efficiency, leads to significant maintenance costs and may cause downtime of turbines with corresponding production losses.

To take adequate measures in design, operation and maintenance of HPPs, the knowledge on turbine wear needs to be improved and relevant parameters have to be quantified. The relevant parameters for hydro-abrasive erosion, such as suspended sediment concentration, size, hardness and shape of particles as well as relative velocity between the flow and turbine parts, turbine geometry and turbine material, have been identified (e.g. Gummer 2009, Winkler et al. 2011). But it is still not fully understood to which extent these parameters contribute to the dominant damages. Monitoring suspended sediment concentrations (SSC) and size distributions (PSD) throughout the year is still not common and the effect of hydro-abrasive erosion on efficiency is only qualitatively known.

In an interdisciplinary project initiated by VAW of ETH Zurich and Hochschule Luzern, the problem of hydro-abrasive erosion is investigated mainly by means of a case study at the existing HPP Fieschertal. The goal of the project is to contribute to a better understanding of interactions between suspended sediment load, turbine wear and efficiency as a basis for economic and environmental optimization (Fig. 1):

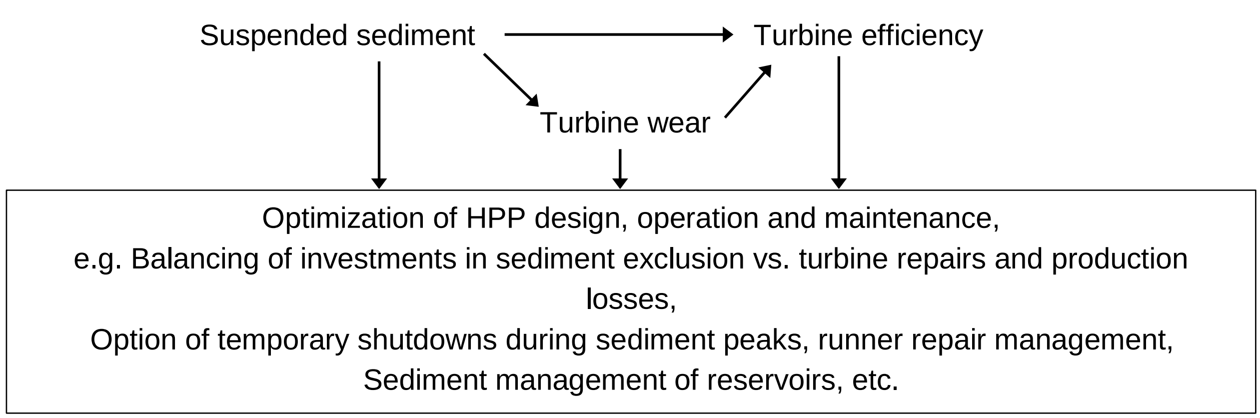

Fig. 1: Knowledge on turbine wear as a basis for optimization of HPPs

The HPP Fieschertal (Fig. 2) is a 509 m net head run-of-river type scheme located in the Canton of Valais in the Swiss Alps. Since the HPP was brought into service in 1976 severe hydro-abrasive erosion at needles, nozzles and runners of the two 32 MW Pelton units has been observed. Although coating of turbines and other hydraulics parts reduced the extent of the damages, sediment handling as well as optimized operation and maintenance of the HPP remain an important economic issue.

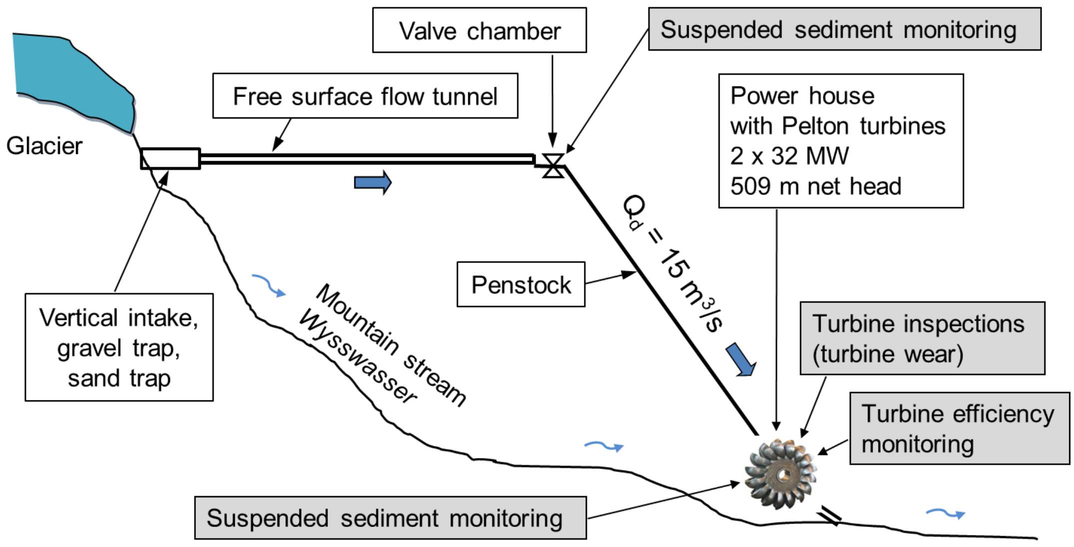

Fig. 2: Schematic overview of the HPP Fieschertal with the investigation program (grey).

This paper presents results from the on-going research project on turbine wear, efficiency and suspended sediment monitoring. Turbine inspections giving indications on turbine wear are documented with photographs, surface mapping using a 3D optical scanner and coating thickness measurements inside selected runner buckets before and after the sediment season. The evolution of turbine efficiency over time is measured by periodical efficiency index tests. Suspended sediment in the turbine water is monitored using various optical and acoustic devices, such as turbidimeters, a laser diffractometer and a method based on acoustic discharge measurement installation (see Felix et al. 2012). In the following sections, the measurement devices, the experimental procedure and the results are presented and discussed.

2. TURBINE WEAR MEASUREMENTS

2.1. 3D digitization

The geometries of selected buckets of Pelton runners were measured with a 3D optical scanning camera (Steinbichler Comet L3D) directly inside the turbine casing (Fig. 3). The working principle of the scanner is based on triangulation. It has a resolution of five megapixels in a measurement volume of 480 x 400 x 250 mm. The 3D point distance is 190 µm and the accuracy of the system is within 25 µm.

Since the surfaces of the buckets (stainless steel) are light reflecting a whitening spray has to be applied prior to the scanning. Furthermore, reference markers are used to improve the matching of point clouds and the measuring accuracy. One full day with a two-men team is required to digitize two buckets including calibration of the sensor before the digitizing.

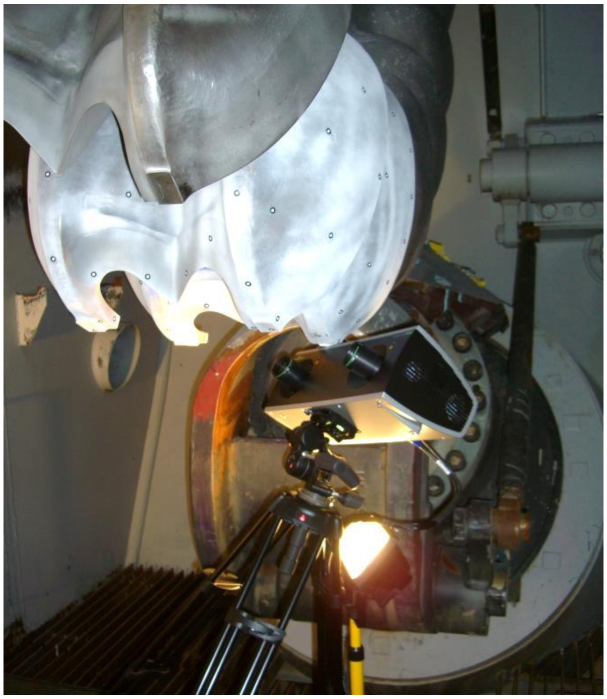

Fig. 3: 3D optical scanning camera used to digitize two selected buckets with reference points.

With regard to wear and efficiency of Pelton turbines the splitters and cut-outs of the buckets are of special importance. Brekke et al. (2002) formulated as a rule of thumb: When the thickness of the splitter has increased to 1 percent of the bucket width, the efficiency drops by 1 percent at full load. The maximum splitter width is practical to measure at turbine inspections. Boes (2009) related the evolution of splitter width with cumulated suspended sediment load.

In Figures 4 to 6, geometrical changes due to hydro-abrasive erosion at splitters and cut-outs, obtained from comparisons of digital geometric models taken before and after the sediment season, are shown.

At the beginning of the sediment season 2012 the runner installed in machine group 1 was fully reconditioned (welding, grinding and complete coating; with geometry close to planned geometry) whereas the runner in machine group 2 has been in use for several seasons after the last factory overhaul and was repaired on site (grinding and local re-coating).

The hydro-abrasive erosion at the splitter (analysed here as height differences along the splitter's longitudinal profile) for the bucket no. 1 of the runners of the machine group 1 and 2 is displayed in Fig. 4. During the sediment season 2012 the splitter height was reduced by about 3 mm after 3426 operating hours at machine group 1 and by 5 mm after 1430 operating hours at machine group 2. In summer 2012 a major flood event with SSC ranging up to approx. 50 g/l occurred when both turbines were running.

The erosion rates 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 (Fig. 5).

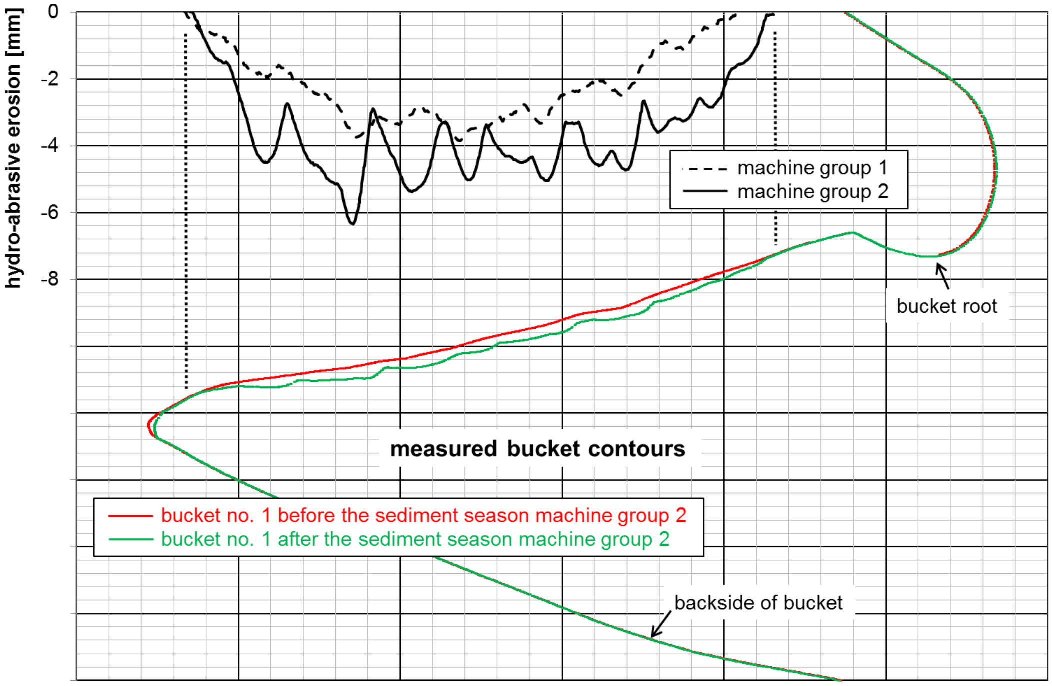

Fig. 4: Side view of the digitized main splitter: Comparison (black) between the splitter geometries of buckets no. 1 of the machine groups 1 and 2 before (red) and after (green) the sediment season.

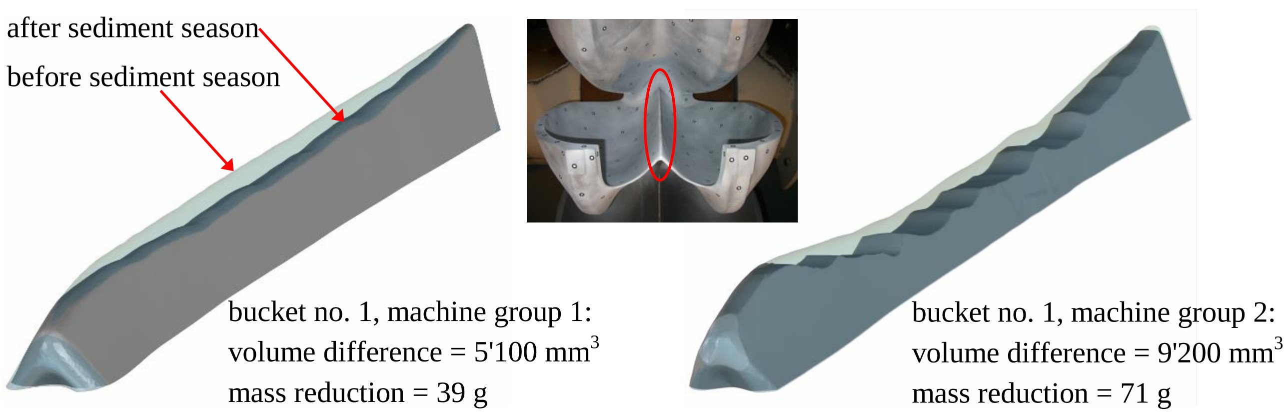

Fig. 5: 3D views of the digitized main splitters (red ellipse): Comparison between the splitter geometries before (transparent) and after the sediment season (grey) of buckets no. 1 of machine groups 1 and 2. The mass reduction is calculated with a density of 7.7 g/cm^3 for the base material.

Further damages occur at the cut-out section of the bucket. The digitized edges of the cut-outs of bucket no. 1 of machine group 1 before and after the sediment season are shown in the lower part of Fig. 6 (top view). The differences in geometry of the cut-outs before and after the sediment season are plotted in the upper part of Fig. 6 for both machine groups. The cut-outs were abraded by up to 9 mm towards the turbine axis at machine group 1 and by up to 6 mm at machine group 2. Interestingly, the erosion measured at the cut-outs exhibits an opposite behaviour compared to the erosion at the splitters.

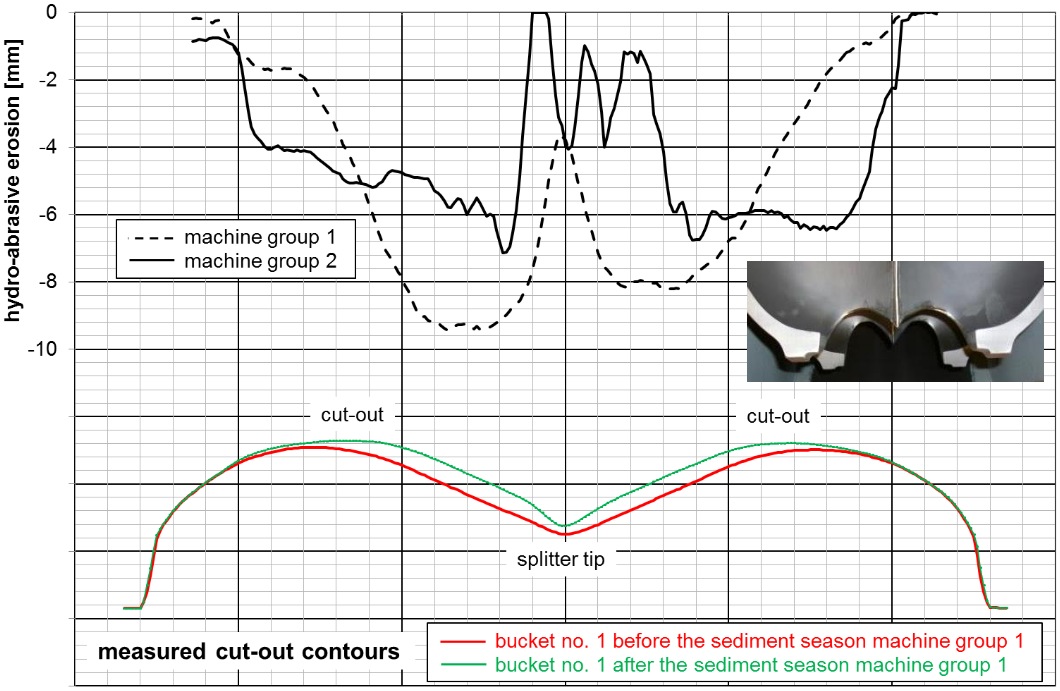

Fig. 6: Top view of the digitized cut-out (with the splitter tip in the centre): Comparison (black) of buckets no. 1 of machine groups 1 and 2 between the cut-out geometries before (red) and after (green) the sediment season.

2.2. Coating thickness measurements

To analyse turbine wear mechanisms and local damages in coated Pelton buckets as installed in the HPP Fieschertal, it is essential to quantify coating thicknesses. Since the coating material (approximate Mohs hardness 7.5) is much harder than the base material (approximate Mohs hardness 4.5) of the Pelton bucket, the erosion potential raises significantly when the coating material is removed locally. Reduced coating thicknesses can result from continuous silt and sand abrasion or from single grain or stone impacts, which may crack the coating surface.

In this on-going project the coating thickness distributions inside selected Pelton buckets before and after the sediment season are measured using a thickness gauge (Helmut Fischer Deltascope FMP30 with dual-tip probe) based on magnetic induction. First spatially distributed thickness measurements using a template that defines the measurement locations within the buckets were completed. An example of such a coating thickness distribution inside a bucket of the runner which has been fully reconditioned before the sediment season is shown in Fig. 7. The distribution was obtained from an interpolation between 153 measurement locations (black points in Fig. 7). At each location, ten repeated measurements were done to achieve a mean value with an expanded measurement uncertainty (at a confidence level of 95 percent) less than 3 percent (average over all measurement locations). As it can be seen from the colour bar, the coating thicknesses vary mainly between 200 and 400 µm with an approximate mean value of 300 µm.

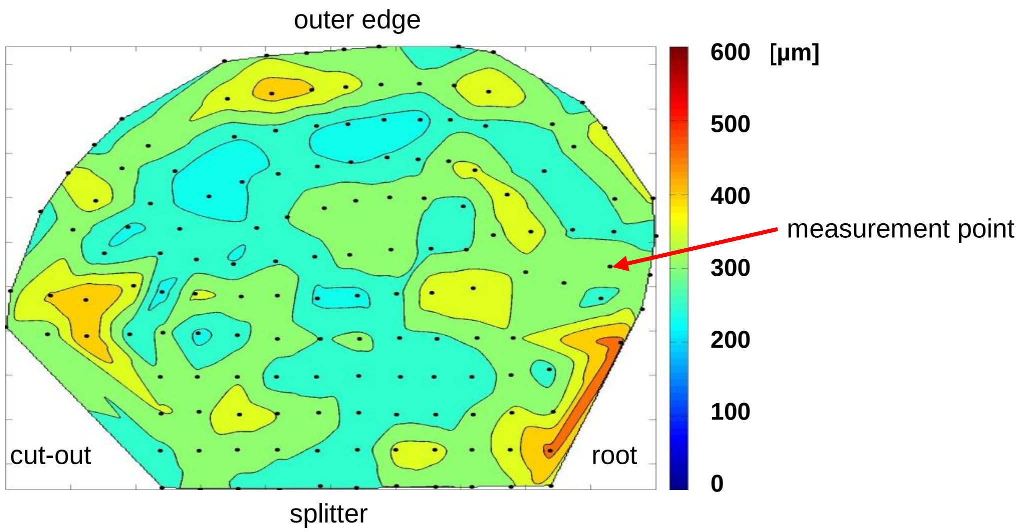

Fig. 7: Coating thickness distribution inside the left half of bucket no. 2 of machine group 1 after the sediment season.

3. EFFICIENCY MONITORING

Turbine wear leads to efficiency reduction. Only a few published data are available (e.g. Dahlhaug et al. 2010 or Bajracharya et al. 2008), describing quantitatively the efficiency decay in defined time intervals, correlated to different turbine damages. One main reason for this lack of published 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. A periodical evaluation of the index efficiency allows thus to quantify the evolution in turbine efficiency. Classical index efficiency measurements encompass a series of measuring points (part load to full load) with constant operating conditions. Accordingly, such measurements are time-consuming. Almquist et al. (1995) introduced the so called "sliding gate method". In this method the guide vanes of a Kaplan turbine were continuously opened and closed while acquiring data for efficiency evaluation. This method can also be adapted to Pelton and Francis turbines, as discussed by Abgottspon and Staubli (2008). Necessary condition for good measurements is that they are performed under quasi-steady conditions. The closing and opening ramps must accordingly be slow enough to fulfil this condition. An example of such a "sliding needle" procedure in the HPP Fieschertal is shown in Fig. 8. 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 of such index tests is that in most cases the instrumentation of the HPP 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 HPP Fieschertal three principal possibilities to calculate the index efficiency are available:

- acoustic discharge measurements at the upper and lower end of the pressure shaft,
- pressure difference measurements in a Venturi pipe section upstream of each machine group, and
- needle stroke measurements.

Redundantly performed measurements and evaluation allow cross-checks and contribute to an increase of the reliability of the evaluated differences in efficiency.

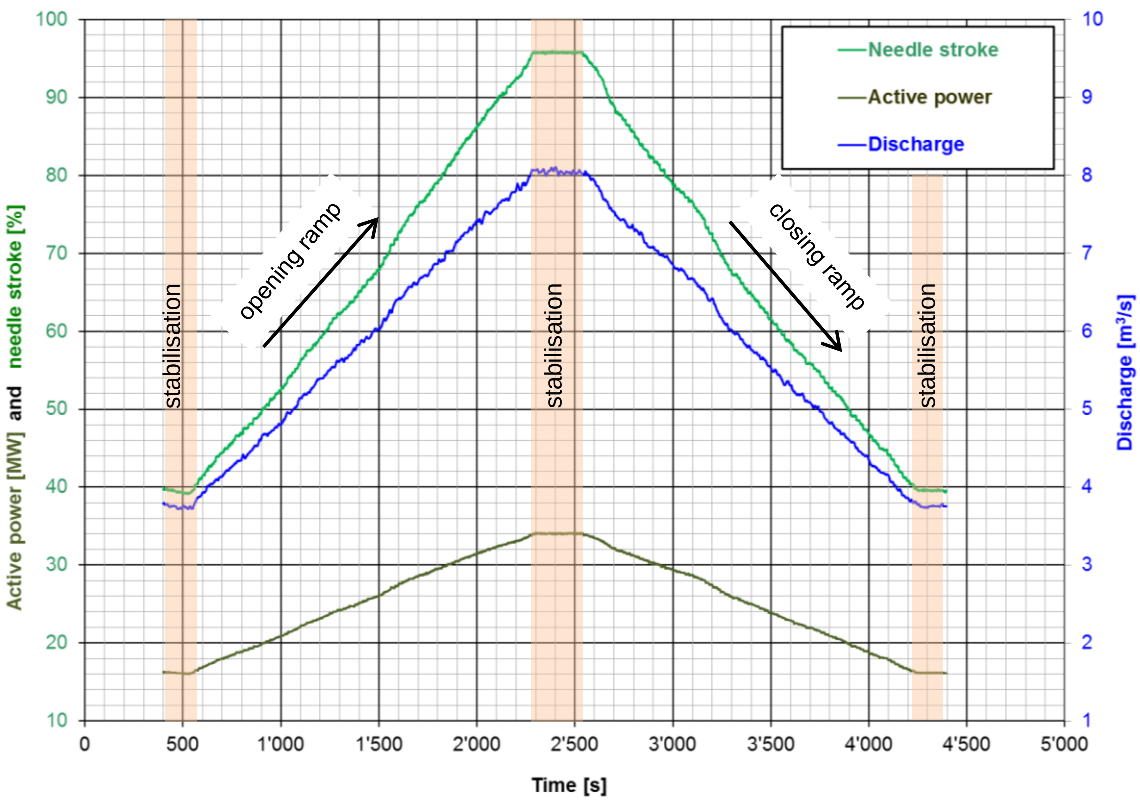

Fig. 8: Active power (dark green, lowest curve), needle stroke (green, highest curve) and discharge (blue, curve in the middle) variation during a sliding needle index efficiency measurement.

Fig. 9 shows the efficiency history of machine group 1, calculated twice (independently) based on the two available acoustic discharge measurements. The differences between the instruments indicate reproducibility within 0.2 percent.

Between the reference measurements of July 4, 2012 and the second measurements of Sept. 27, 2012 more than half of the sediment season passed. An index efficiency decrease of 0.9 percent is obtained. This decrease is attributed to hydro-abrasive erosion. On Nov. 5, 2012 none or only a minor rise in the index efficiency level is found compared to the previous measurement, i.e. the index efficiency level remained constant. This agrees with the suspended sediment load which is measured to be low during this period. In the period until the next measurement of March 8, 2013 very low suspended sediment concentrations were measured. The observed index efficiency level rise of up to 0.5 percent can be explained with maintenance works carried out at the main splitters of the Pelton buckets during winter.
In order to distinguish the effects of hydro-abrasive erosion or of maintenance works at relevant turbine parts on turbine efficiency, index tests are required as close as possible before and after such works.

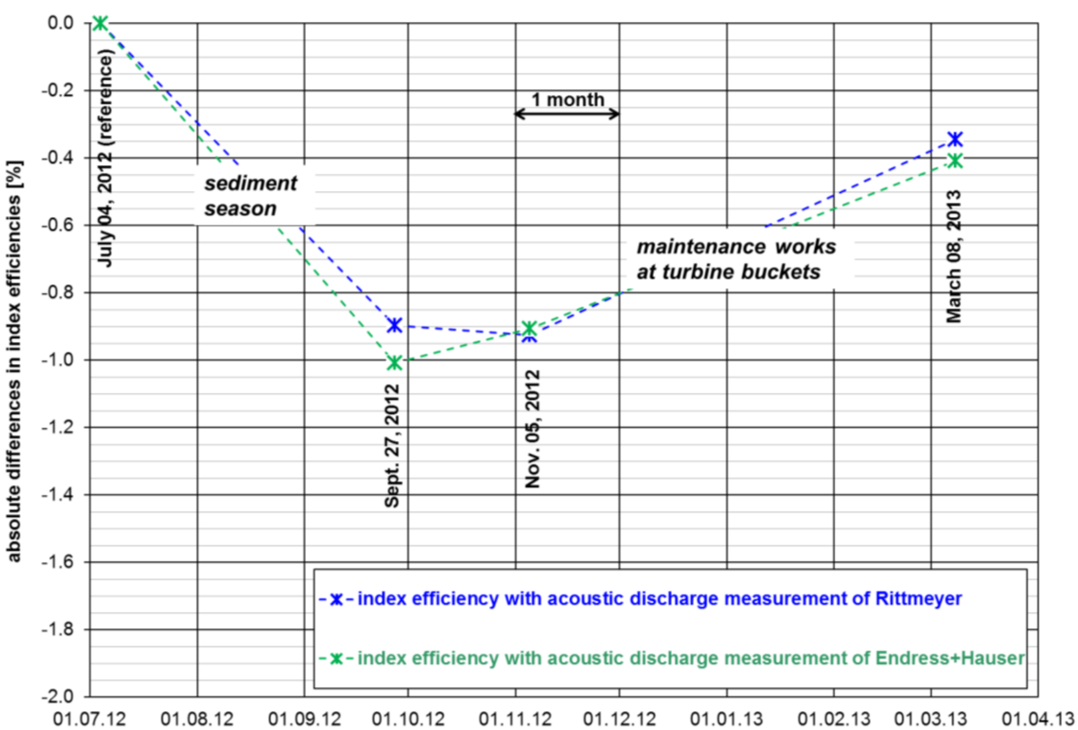

Fig. 9: History of the index efficiency for machine group 1: Absolute differences from weighted index efficiency levels with two different acoustic discharge measurement devices (blue: Rittmeyer crossed 4-path inside mount, green: Endress + Hauser 1-path clamp-on outside mount)

4. SUSPENDED SEDIMENT MONITORING

Among the available techniques for suspended sediment monitoring (SSM) turbidimeters are most popular, despite the fact that their calibration is strongly particle-size dependant and the calibration needs generally to be established by the user (Wren et al. 2000). Various kinds of turbidimeters (measuring optical transmission or scattering) have been used in the present study. An acoustic method for SSM based on installations for acoustic discharge measurement (ADM) is also applied (single frequency attenuation, see also Costa et al. 2012). Furthermore, a portable laser diffractometer (LISST) is used (Agrawal and Pottsmith 2000). The latter yields not only estimates of SSC, but also of PSD. Particle size is an important parameter in the context of turbine wear.

The devices for SSM used in this study are summarized in Table 1. In a first phase of the project, these devices were tested in the mixing tank in the hydraulic laboratory at Hochschule Luzern, Competence Centre for Fluid Mechanics and Hydro Machines. In summer 2012 they were installed at the study HPP (locations see Tab. 1 and Fig. 2). Most devices are installed in the valve chamber, at the inlet to the penstock. Further information on these devices, the laboratory tests as well as the installation at the study HPP and previous results are described by Felix et al. (2012) and Abgottspon (2011).

In addition to the devices for continuous real-time SSM, an automatic water sampler was installed in the valve chamber and the obtained samples are analysed in the laboratory as a reference for the other devices. Reference SSCs are determined by weighing of the solid residues (primary method). The sampler is programmed to take one sample every 2 days and is additionally triggered by the signal of a turbidimeter to increase the sampling rate during relatively high SSC.

Device type	Device model and manufacturer	Device output and measuring principle	Derived parameters	Installed in HPP Fieschertal at
Turbidimeter, submerged	*Turbimax W CUS41* Endress-Hauser	Turbidity [FNU] from backscatter	SSC	Intake (starting 2013)
	Solitax ts-line sc Hach-Lange	Turbidity [FNU] from backscatter	SSC	Tailrace channels of each unit
Turbidimeter, in-line	*TurbiScat (90°, 25°)* Sigrist Photometer	Turbidity [FNU] from backscatter	SSC	Valve chamber, at the inlet to the penstock
	TF16-N with F20 Optek Danulat	Turbidity [CU] from transmission	SSC	
Acoustic method	*Risonic Modular* Rittmeyer	Received amplitude [V] forward scattering	SSC	
Portable laser diffractometer	*LISST-100X, Type C* Sequoia Scientific	Volume concentrations in 32 size classes [ppm]	SSC and PSD	

Table 1: Devices used for continuous suspended sediment monitoring.

The time series of SSC in the turbine water obtained from the devices installed in the valve chamber are shown in Fig. 10 for the period from July 2012 to the end of the sediment transport season. The conversion (calibration) from original units of the devices (e.g. FNU) to SSC is based on the reference SSCs collected so far at the study site.

The time series of the in-line turbidimeter (optical backscatter and optical transmission) models used here show considerable drift. Their signals are increasingly biased by particles that accumulated on the optics in the flow-through cells and by bio-fouling. Flushing of the flow cells by increasing the discharge of the sampling line for some minutes was not sufficient to clean the optics. Only manual cleaning (at day 303) brought the signals back to the low level expected for the relatively clear water in late autumn. In the sediment season 2013 another turbidimeter model, measuring the turbidity at a free falling jet (*AquaScat* from Sigrist Photometer), will be installed at the sampling line in order to avoid signal drift and frequent manual cleaning. At the two turbidimeters installed at the tailrace channels no problem of signal drift occurred since those submerged turbidimeters are equipped with a wiper that keeps their optics clean.

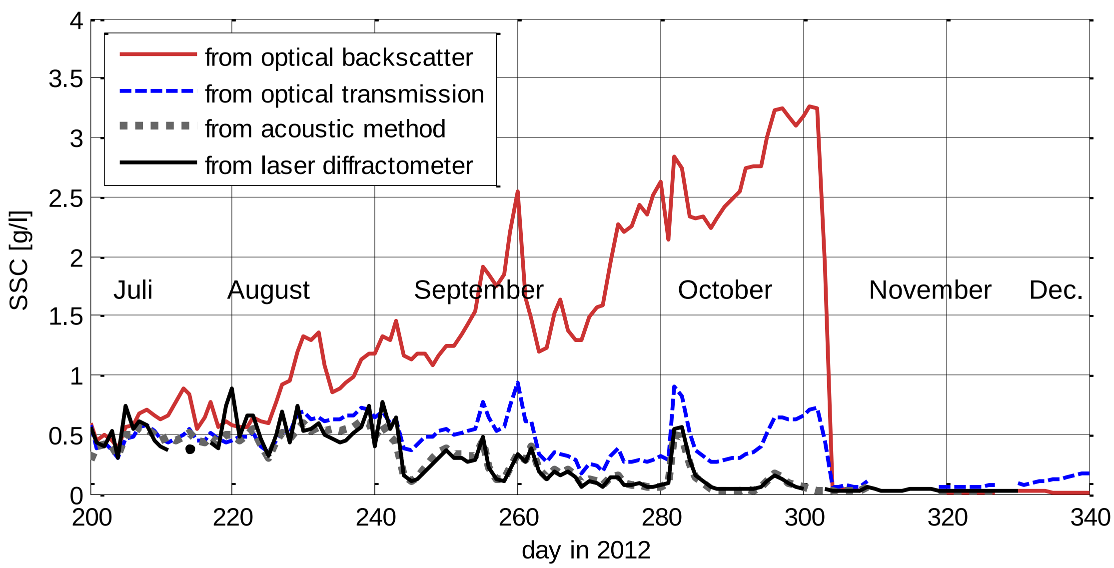

Fig. 10: Time series of daily averaged SSC in the turbine water, obtained from various devices installed in the valve chamber, from July, 19 (day 200) to December, 6 (day 340) in year 2012.

Figure 11 shows a close caption of Figure 10 as an example of suspended sediment transport during three summer days. In addition, 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 (d_{50}, i.e. the median diameter by mass) obtained from the LISST (right axis) are also shown in Fig. 11. Data were recorded every second for turbidimeters and the acoustic method and every minute for the LISST. The time series were smoothed by moving average over 20 minutes and implausible data were discarded. Trends and offsets visible in Fig. 10 were removed from the turbidimeter data.

During summer days SSC was approx. 0.5 g/l and the time series from all devices (turbidmeters, laser diffractometer and acoustics) show similar behaviour, except for a sediment transport peak in the early morning hours of day 239. During this event the LISST yields a higher SSC compared to the other continuous measuring methods. The LISST measurement is supported by the reference measurement taken during the rising limb of the SSC peak. From Figure 11 it can be seen that the median size of the particles in the turbine water is approximately 15 microns, except for the phase of increased sediment transport. During this phase, about three times coarser particles (d_{50} approximately 45 microns for some hours) were transported. The maximum of d_{50} occurred approximately one hour after the maximum in SSC.

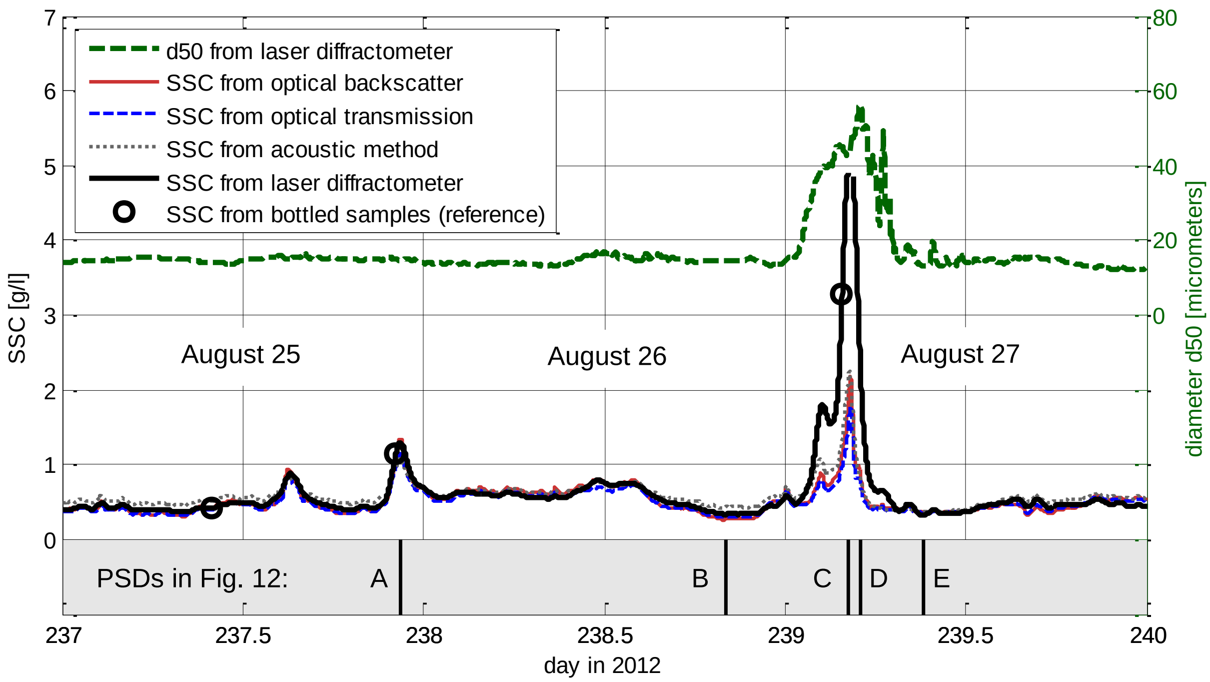

Fig. 11: Time series of SSC in the turbine water, from devices as in Figure 10, reference SSCs from bottled samples, and time series of d_{50} obtained from LISST; example of three summer days (August 25 to 27, 2012).

In Figure 12 selected PSDs obtained from the LISST are displayed. The times at which these PSDs were measured are indicated in Fig. 11 with capital letters. 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 d_{50} (D) are considerably coarser.

The underestimation of SSC by the turbidimeters and the acoustic method (single frequency forward scattering) in times with transport of coarser particles is related to their physical operating principle. Coarser particles do not cause as much turbidity or scattering as finer ones (at same SSC). The calibration of those devices depends strongly on particle size, for which in practice a constant time-averaged value has to be adopted. As it can be seen from Figures 10 and 11, 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. In the rest of the time, however, those devices provide quite accurate SSC estimates.

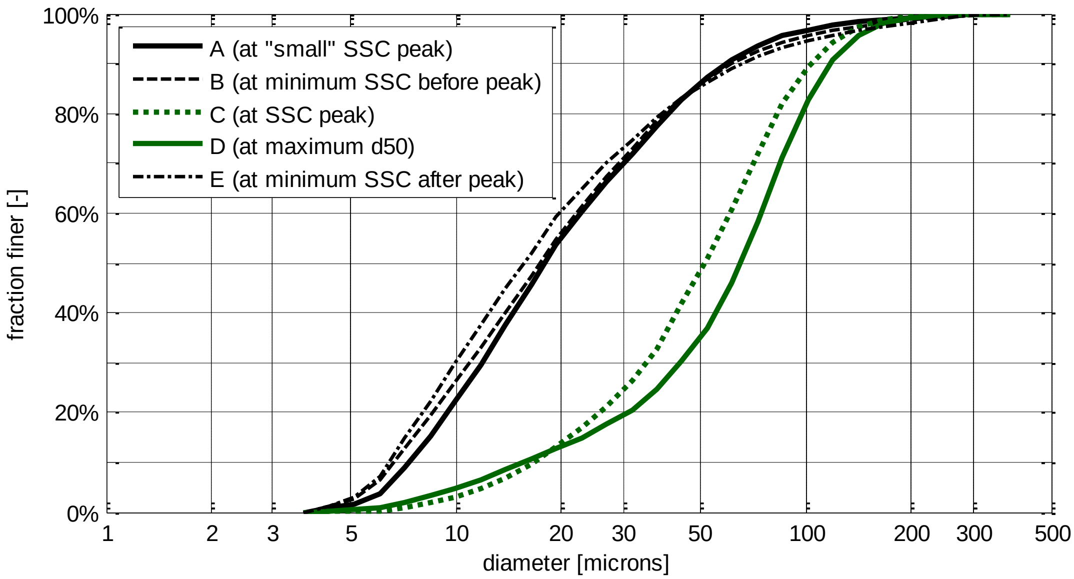

Fig. 12: Selected PSDs obtained from LISST, measured in the turbine water at times indicated in Fig. 11.

5. CONCLUSIONS

First analyses of the hydro-abrasive erosion rates for both machine groups in the HPP Fieschertal, Switzerland, showed that single events such as heavy rains lead to major material loss at Pelton buckets. Therefore, temporary shutdowns of the HPP would help to prevent excessive hydro-abrasive erosion during such events. To do so, a reliable method for continuous real-time measurement of suspended sediment load is needed.

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

Since frequent manual cleaning of measuring devices is not practical, turbidimeters with an automatic cleaning system (wiper or pressurized air) or turbidimeters with optics not in contact with the sediment-laden flow (free falling jet type) are recommended, even in cold and relatively nutrient-poor water of mountain streams. The acoustic method based on ADM installations existing in many HPPs offers the advantage of monitoring suspended sediment directly in the penstock. Among the devices used here, LISST offers new possibilities for SSM, since it provides not only information on SSC, but also on PSD. In environments with variable particle sizes LISST measures SSC more accurately than devices with a fixed calibration depending on particle size. For a better understanding of hydro-abrasive erosion, measuring PSD is important since coarser particles have higher abrasion potential (for a given SSC) and are therefore particularly harmful to turbines. Devices with particle size-dependant calibration may be used as pragmatic contributions to a real-time decision making system for the operation and maintenance of HPPs, especially for smaller schemes.

In summer 2012 SSC of approximately 0.5 g/l with d_{50} of normally 15 microns was observed in the turbine water of HPP Fieschertal. The measurements confirmed that SSC and PSD may vary strongly within short time, e.g. due to precipitation events, to SSC of up to approximately 50 g/l and d_{50} of e.g. 45 microns.

Wear at coated Pelton runner buckets was measured with a 3D optical scanner and a thickness gauge. 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 analysis showed that the splitter height decreased 3 to 5 mm during the sediment season 2012, this corresponds to approximately 0.5 to 0.8 percent of the inner bucket width of 650 mm. The hydro-abrasive erosion at the splitter is influenced by the splitter geometry at the beginning of the sediment season, particle load and the operating hours. Local coating thicknesses in the bucket of a Pelton runner were measured with a thickness gauge based on magnetic induction.

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 of the investigated turbines the efficiency decrease was 0.9 percent for half of the sediment season 2012. In order 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 turbine efficiency, index tests should be performed before and after such works. Redundantly performed index measurements and evaluation allows cross-checking and increasing the reliability of the evaluated differences in efficiency.

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Measuring Turbine Abrasion and Efficiency Decrease: First Results of the Case Study at HPP Fieschertal

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Abstract

Besides siltation of reservoirs, wear on turbines of hydroelectric power plants (HPP) is an economically important issue related to sediment-laden natural waters. Hydro-abrasive erosion on turbines that is caused by suspended sediment may lead to considerable 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 can be local or extensive area damages due to abrasion or secondary cavitation. The location of such damages is influenced by the local flow field, which itself is affected by progressive wear. 3D digitizations (measurements) of selected Pelton buckets allow quantifying material losses at relevant parts like the main splitter and the cut-out section. The paper shows different possibilities to quantify such material losses, e.g. reduction of height, increase of width and volume differences at the main splitter, and geometrical changes at the cut-outs. Erosion rates determined over one sediment season at the HPP Fieschertal lie 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. The erosion is influenced by the initial geometry of the Pelton bucket and the sediment load (particle concentration, size distribution, mineral composition and particle shape) during the operating hours.

Changes in efficiency were evaluated based on periodical measurements with the sliding needle index measurement method. A decrease in efficiency of 0.9 percent for a little more than half of the sediment season 2012 was observed at one runner. Due to maintenance works on that runner during the winter the efficiency increased 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.

This paper focuses on wear at Pelton buckets and associated turbine efficiency decrease, whereas the corresponding paper by Felix et al. (2013) treats measurements of suspended sediment at the same HPP.

1 Introduction

Hydro-abrasive erosion has a detrimental effect on efficiency, leads to significant maintenance costs and may cause downtime of turbines with corresponding production losses. To take adequate measures in design, operation and maintenance of HPPs, the knowledge on turbine wear needs to be improved and relevant parameters have to be quantified. Few quantitative studies on the interrelations of suspended sediment, turbine wear and efficiency are available, especially for Pelton turbines. Laboratory tests of hydro-abrasive erosion on turbine parts (Winkler et al. 2011) contribute to a better understanding, e.g. of the influence of particle size. Complementary to this, measurements at full scale conditions are required.

For this reason, an interdisciplinary project by VAW of ETH Zurich and Hochschule Luzern was initiated in order to investigate hydro-abrasive erosion by means of a case study at the HPP Fieschertal. The HPP Fieschertal (Fig. 1) is a 509 m net head run-of-river type scheme located in the Canton of Valais in the Swiss Alps. From the time of first operation in 1976 till today severe hydro-abrasive erosion at needles, nozzles and runners of the two 32 MW Pelton units occurred. In the past decades an increase of fine sediments has been observed due to glacier retreat and increased variation in precipitation. Although coating of turbine parts increases the time between overhauls, sediment handling as well as optimized operation and maintenance of the HPP have remained important economic issues. One operational option studied in this project is to switch-off the turbines during suspended sediment peaks in case the costs caused by turbine wear exceed the benefits from power sales.

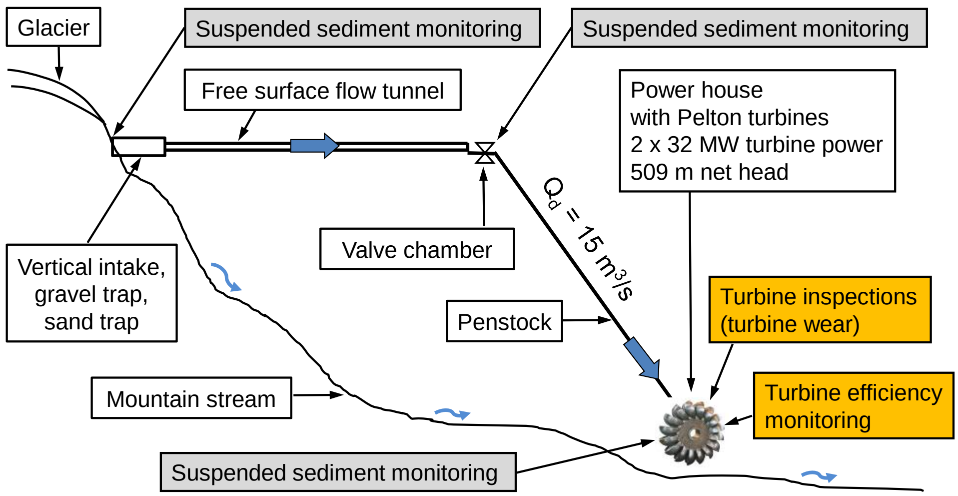

Fig. 1: Schematic longitudinal profile of the case study HPP Fieschertal.

In this paper, wear at buckets of Pelton turbines measured over the sediment season 2012 at this HPP and efficiency decreases measured until early summer 2013 are presented (components of the study highlighted in Fig. 1). The corresponding paper by Felix et al. (2013) describes methods and selected results of suspended sediment measurements at this HPP in the same period.

2 Turbine wear determination

2.1 Analysis method

Turbine wear was determined by comparing geometries of Pelton buckets measured before and after a period during which the turbines were operated with sediment-laden water. Geometrical models of Pelton buckets were determined using an optical digitizing system. The used system has a resolution of five megapixels in a measurement volume of 480 x 400 x 250 mm. The 3D point distance is 190 µm and the accuracy of the system is within 25 µm. Digitizing two buckets of an installed runner (in the turbine casing) requires one full working day of a two men team. Prior to digitizing, the system was calibrated to the prevailing temperature.
As the main splitter and the cut-outs of Pelton buckets are known to be relevant for turbine wear and performance, the focus of the analysis of turbine wear is set to these parts.

2.2 Definitions

2.2.1 Local coordinate system in the Pelton bucket

In order to compare the geometries of Pelton buckets measured in a series of turbine inspections, a consistent and reproducible geometrical reference has 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. 2 are normally 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 is 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 is set to the intersection of plane B with the outer radius ra (plane C).

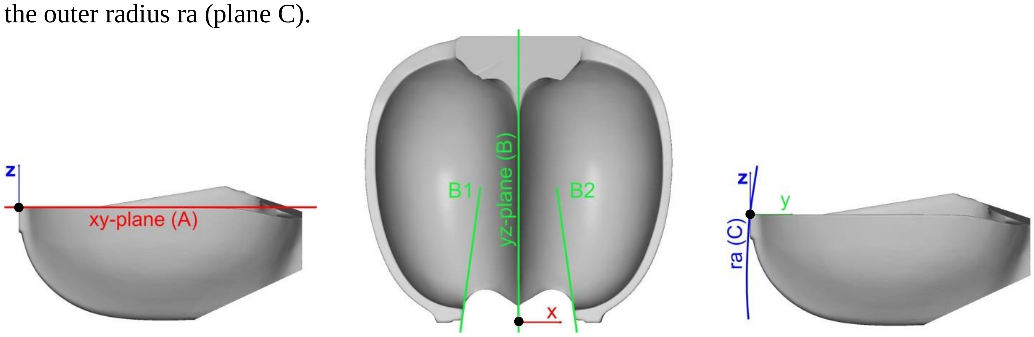

Fig. 2: Digitized Pelton buckets and definition of the coordinate system.

2.2.2 Main splitter height reduction *h*

One way to analyse 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. 3). 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. 3). 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 Figure 3 and were used in all analysis related to the main splitter.

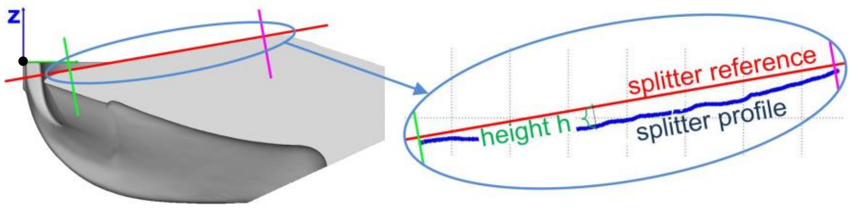

Fig. 3: Definition of eroded splitter height of a Pelton bucket.

2.2.3 Main splitter width *w*

Another way to monitor turbine wear is measuring the width of the main splitter. An increase of splitter width is known to be associated with efficiency decrease (e.g. Brekke et al. 2002). Boes (2009) considered the width of the main splitter as a key parameter describing hydro-abrasive erosion at a Pelton runner. If a coated splitter is eroded the splitter width is clearly visible because of its flat top surface and with sharp edges to the flanks of the splitter. In case of a splitter top with rounded cross section, however, the definition of splitter width is not obvious, also 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). Figure 4 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 Figure 4. The plotted gradients were set to zero if the gradient was steeper than this limit.

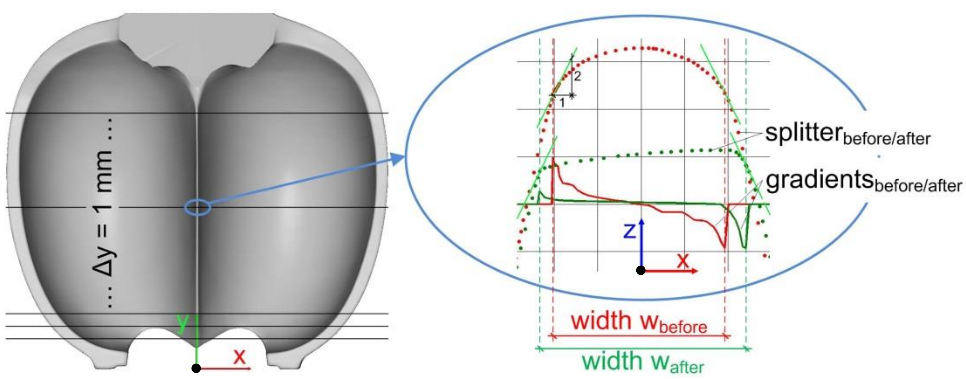

Fig. 4: Definition of the main splitter width of a Pelton bucket.

2.2.4 Cut-out depth *d*

The hydro-abrasive erosion at the cut-out section is determined as difference in the cut-out depths measured at various times. 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. 5). 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 easily reproducible. To calculate the differences in cut-out depths no interpolation is needed thanks to using the same locations of the cross sections.

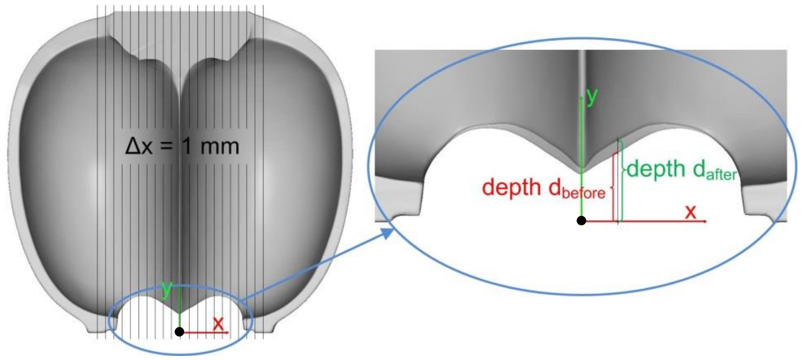

Fig. 5: Definition of the cut-out depth at a Pelton bucket.

2.3 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 analysed 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 of Fieschertal, which produced a flood discharge with an estimated return period between 10 and 30 years (Felix et al. 2012). 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.

	machine group 1	machine group 2
date of first measurement	Mai 2012 before sediment season	April 2012 before sediment season
number of sediment seasons in operation since last factory overhaul	0	3
actual runner condition	fully reconditioned at factory, including new coating	after annual on-site revision (grinding and local recoating)
date of second measurement	February 2013 after sediment season / before next sediment season	August 2012 during sediment season, taken out of operation
number of sediment seasons in operation since last factory overhaul	1	3.5
actual runner condition	"usual wear"	"heavy wear"

Table 1: Dates of turbine geometry measurements and respective runner conditions at HPP Fieschertal.

2.4 Results of Pelton turbine wear measurements

In this section, results of the bucket geometry measurements are given for the parameters as defined in section 2.2 (h, w and d). The following plots include geometrical properties measured before and after the sediment season as well as calculated differences (Δh, Δw and Δd). 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.

Figure 6 shows the shapes of the four examined main splitters before and after the sediment season. Comparing the machine groups, a great difference in the initial conditions can be seen. With a similar splitter height reduction on both machines (see Fig. 7) the volume differences at machine group 2 are considerably greater since the width of the splitter increases as erosion progresses. The mean 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. It is advisable to digitize at least two buckets per runner to get a reliable mean value.

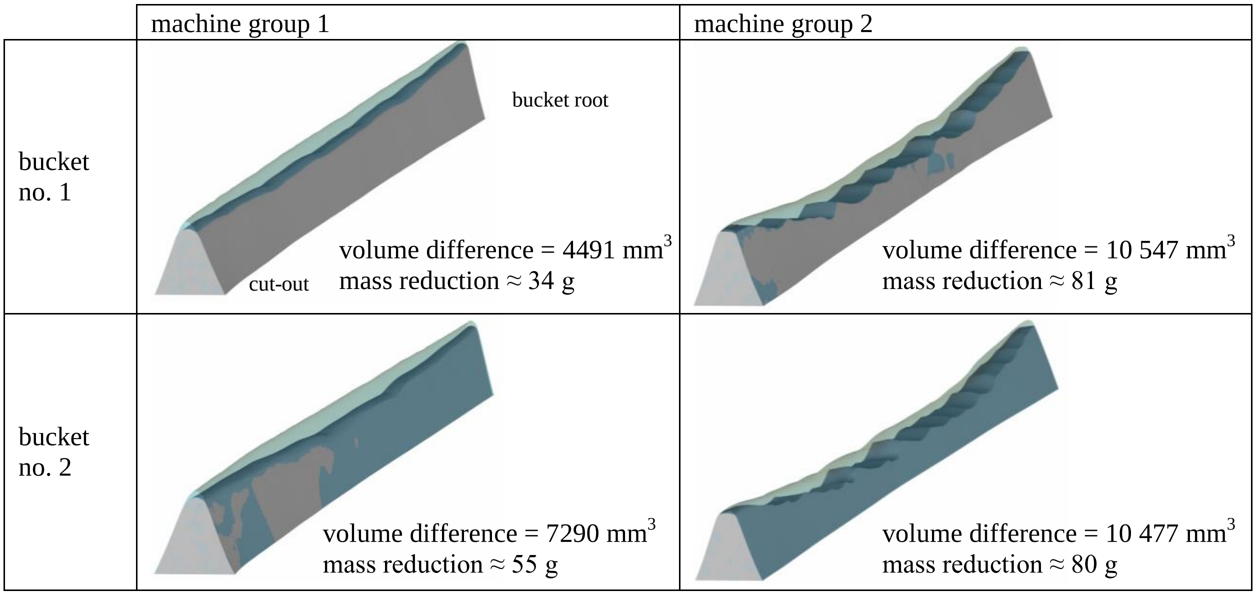

Fig. 6: 3D views of the digitized main splitters: Comparison between the splitter geometries before (transparent) and after the sediment season (grey).

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. 7). 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).

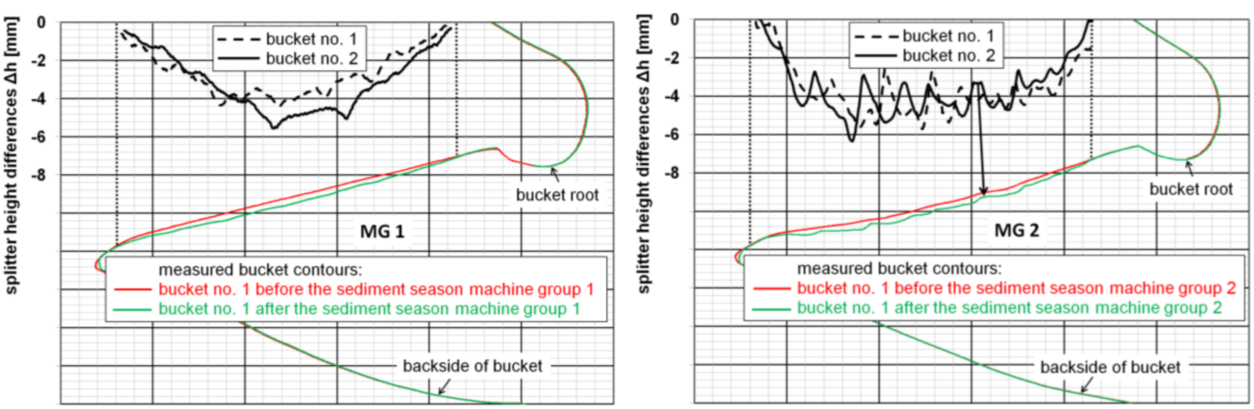

Fig. 7: Side view of the main splitter for machine group 1 (left) and 2 (right): Red and green lines show splitter profiles before and after the sediment season for bucket 1, black lines indicate the differences (erosion heights Δh) for buckets 1 and 2.

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. 8). 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.

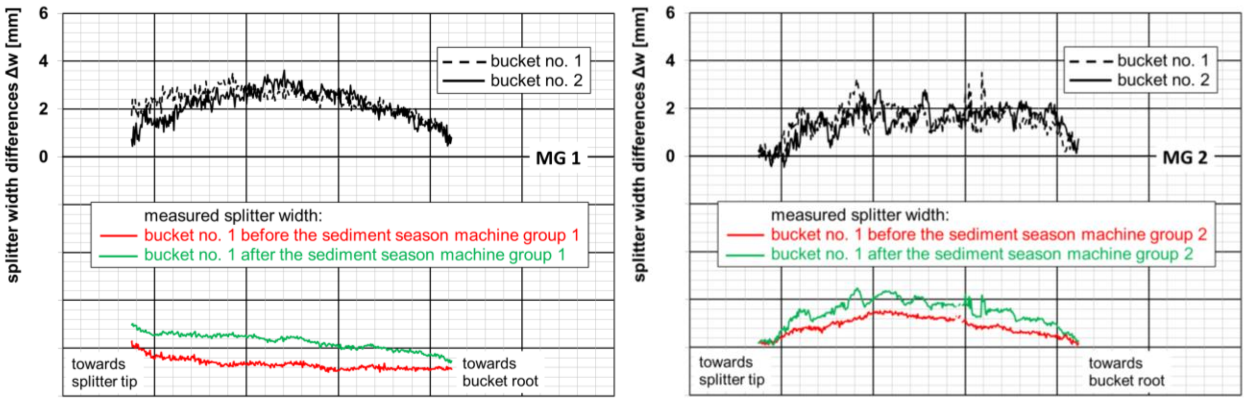

Fig. 8: Splitter widths along the main splitter for machine group 1 (left) and 2 (right): Red and green lines in the lower parts of the diagrams show splitter widths before and after the sediment season for bucket 1, black lines indicate the differences (Δw) for buckets 1 and 2

Further damages occur at the cut-out section of the Pelton bucket. The top views of bucket no. 1 for both machine groups are shown in Fig. 9. The shape of the cut-outs differs considerably between both units (compare the green and red lines left and right in Fig. 9). The shape of cut-outs is influenced by the different number and extent of revisions (grinding and welding) performed at the runners. The increase in cut-out depth Δd 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.

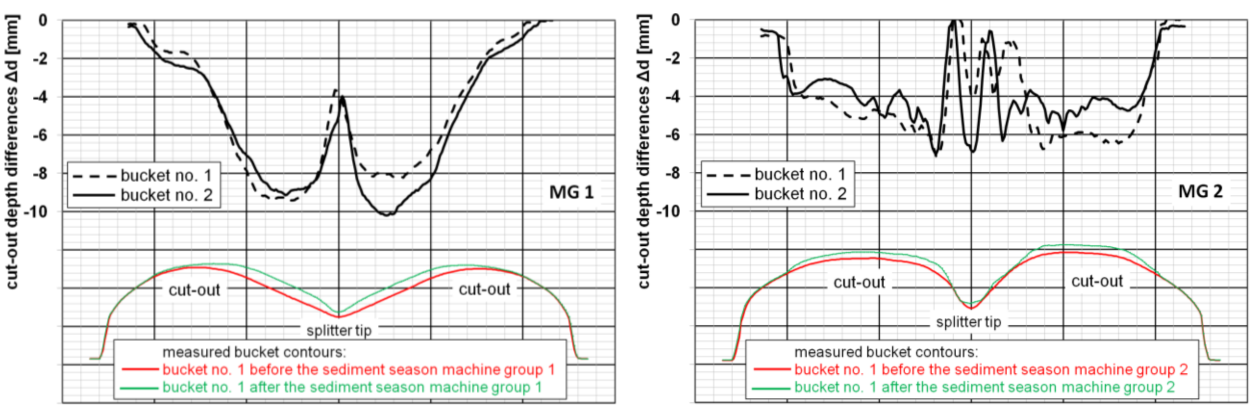

Fig. 9: Top view of the digitized cut-out for machine group 1 (left) and 2 (right): Red and green lines in the lower parts of the diagrams show the cut-out contours before and after the sediment season for bucket 1, black lines indicate the differences in cut-out depths (Δd) for buckets 1 and 2.

3 Index efficiency measurements

Turbine efficiency history at HPP Fieschertal is measured using the periodical sliding needle index measurement method (Abgottspon et al. 2013). “Sliding needle” stands for a gradual variation of turbine discharge between part load and full load during the measurement in case of Pelton turbines. In case of e.g. Francis turbines, the corresponding procedure is called “sliding gate” (Abgottspon & Staubli 2008, Almquist et al. 1995). Measurements involve basically 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 Figure 10 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 (at point A for machine group 1 and at point D for machine group 2). No absolute efficiency differences among both units can be analysed from the diagrams below.

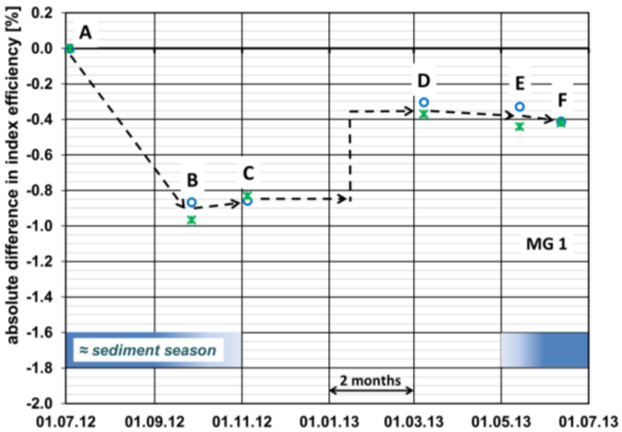

Fig. 10: History of index efficiency for machine group 1 (left) and 2 (right): Absolute differences from weighted index efficiency levels based on two different acoustic discharge measurement devices (circles: Rittmeyer crossed 4-path inside mount, crosses: Endress + Hauser 1-path clamp-on outside mount).

In Table 2 measured efficiency differences for both machine groups are given (mean values of both evaluations based on different discharge measurements). 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 (2013), particle load is defined as the integral of the product of suspended sediment concentration and weighing factors for particle size, shape and hardness over time. Particle load will be quantified based on suspended sediment measurements.

	A → B	B → C	C → D	D → E	E → F
sediment load	high	low	very low	low	low to medium
works on buckets	-	-	grinding	local re-coating	-
efficiency difference machine group 1	-0.9 %	+0.05 %	+0.5 %	–0.05 %	–0.05 %
efficiency difference machine group 2	-	-	-	–0.1 %	0 %

Table 2: Differences in index efficiencies related to sediment load and mechanical works.

The index efficiency decrease of 0.9 percent for machine group 1 is attributed to hydro-abrasive erosion. As mentioned in section 2.3 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. Minor efficiency differences of less than 0.2 percent shall be interpreted with care, since they are of the same order of magnitude as the reproducibility of 0.2 percent which can be reached with the two available acoustic discharge measurements (except one measurement, point F for machine group 2 in Fig. 10).

4 Conclusion and Outlook

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 calculated. For the main splitter, the reduction in height, increase of width and lost material volume were defined and evaluated, 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.
Measurements of turbine wear and efficiency will be continued together with measurements of suspended sediment in the power waterway (see paper by Felix et al. 2013). It is planned 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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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.

By André Abgottspon, Thomas Staubli, David Felix, Ismail Albayrak and Robert M. Boes

Andre Abgottspon is a research assistant and Thomas Staubli is a professor of fluid mechanics and hydro machines with the Competence Centre Fluid Mechanics and Hydro Machines at Hochschule Luzern. David Felix is a PhD student, Ismail Albayrak, PhD, is a research scientist and Robert Boes is a professor of hydraulic structures and director of the Laboratory of Hydraulics, Hydrology and Glaciology at the Swiss Federal Institute of Technology Zurich.

This article has been evaluated and edited in accordance with reviews conducted by two or more professionals who have relevant expertise. These peer reviewers judge manuscripts for technical accuracy, usefulness, and overall importance within the hydroelectric industry.

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[1] — 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 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.

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.[2] 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

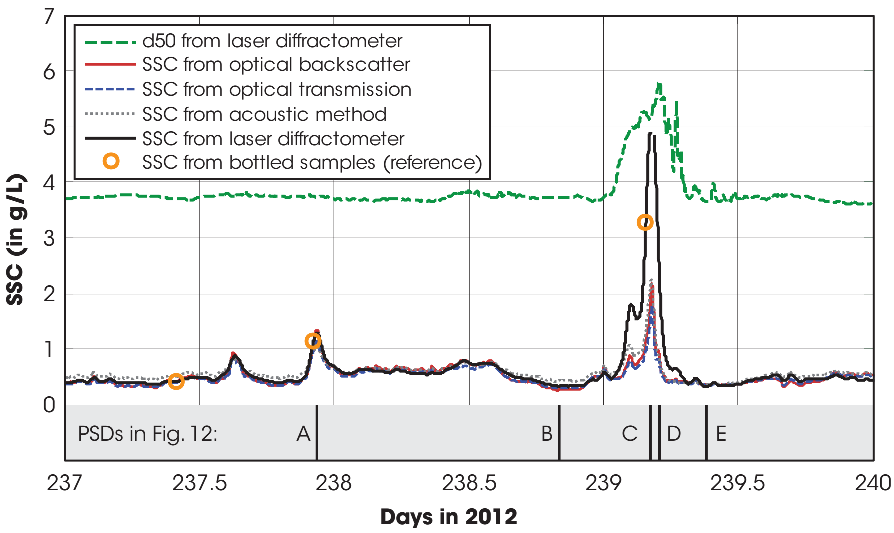
The sediment load passing through the turbines can be quantified as described in the literature.[3] The so-called particle load is calculated from SSC, operating hours and weighting factors for particle size, shape and hardness.

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.[4] 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).[5] Furthermore, a portable laser diffractometer (LISST) is used[6] to estimate SSC and PSD. Particle size is an important parameter in the context of turbine wear.

In a first phase of the project, the SSM devices

Figure 1 — Time Series of SSC in Turbine Water



This time series of suspended sediment concentration in the water running through the turbines at the Fieschertal plant provides an example of suspended sediment transport during three summer days in 2012.

were tested in the mixing tank 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.

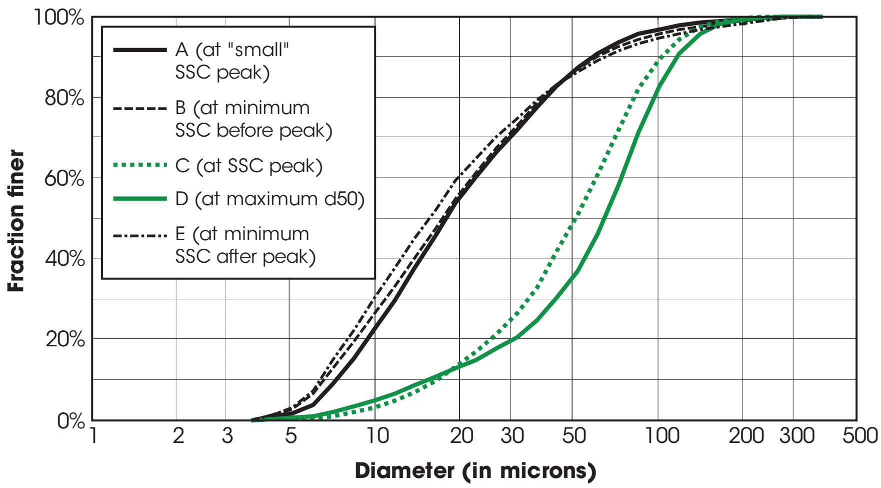
The underestimation of SSC by the turbidimeters and the acoustic method in the times with transport of coarser particles is related to their physical operating principles. Coarser particles do not cause as much turbidity or scattering as finer ones (at the same SSC). The calibration of those devices 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.[9]

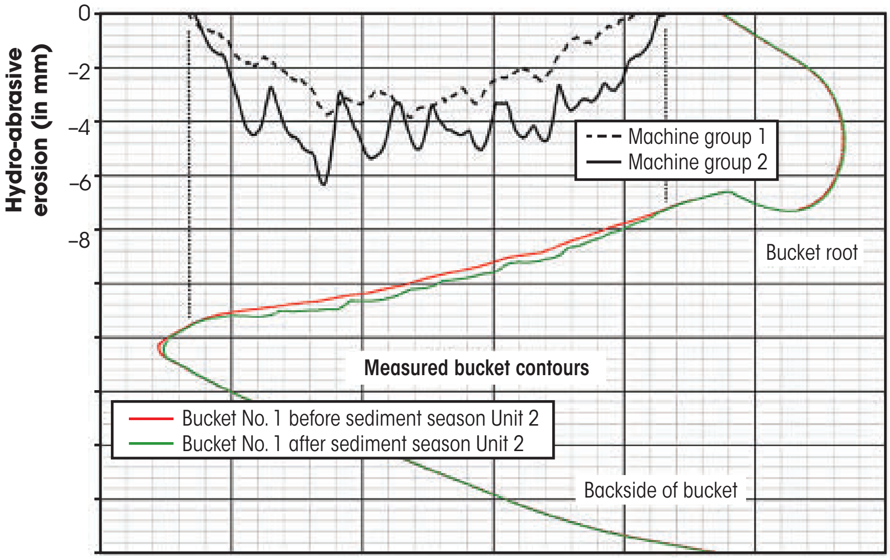
The geometries of selected buckets of the runners at Fieschertal were measured using a 3D optical scanning camera inside the turbine casing. Because the stainless steel buckets reflect light, a whitening spray was applied prior to scanning. Reference

Figure 2 — PSDs Obtained from Laser Diffractometer



Selected particle size distributions measured in the turbine water at times indicated in Figure 1 show that particle size varied significantly over time.

Figure 3 — Side View of Digitized Main Splitter



Comparison (black) between the splitter geometries of Bucket 1 of Units 1 and 2 before (red) and after (green) the sediment season reveal a reduction in splitter height on both units.

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[10] 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;

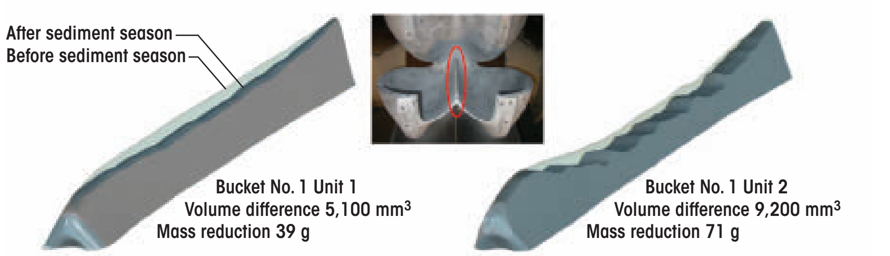
— Pressure difference measurements in a Venturi pipe section upstream of each machine group; and

— 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%.

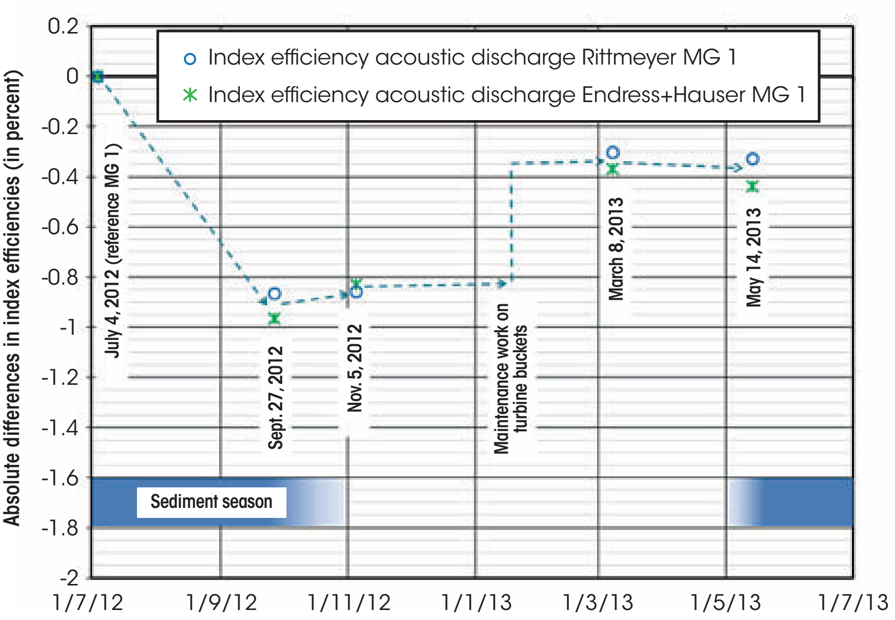
Between the measurements of July 4, 2012, and Sept. 27, 2012, more than half of the sediment season passed. An index efficiency decrease of 0.9% was obtained, attributed to hydro-abrasive erosion. On Nov. 5, 2012, none or only a minor rise in

Figure 4 — 3D views of Digitized Main Splitters



This three-dimensional comparison between the splitter geometries before (transparent) and after (gray) the sediment season for Bucket 1 of Units 1 and 2 shows the change in volume and mass.

Figure 5 — Index Efficiency History for Unit 1



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 level was found. This agrees with the low SSC during this period. Until the next measurement of March 8, 2013, very low SSC was measured. The observed index efficiency level rise of up to 0.5% can be explained with maintenance work carried out at the main splitters of the Pelton buckets during winter and is confirmed by further measurement.

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.

To deal with hydro-abrasive wear during the design, operation and maintenance of hydro plants, knowledge of turbine wear needs to be improved and relevant parameters need to be quantified.

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Notes

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