Measuring techniques to cope with hydro-abrasive erosion of turbines

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Abstract

Hydro-abrasive erosion of hydraulic turbines is an economically important issue due to maintenance costs and production losses. The topic is of particular importance at high- and medium-head run-of-river hydropower plants (HPPs). To address this issue, a comprehensive research study has been conducted at the case study HPP Fieschertal, in the Alps of Switzerland since 2012. The HPP is equipped with two horizontal-axis Pelton units, each with 32 MW nominal power. The injectors and the buckets are hard-coated.
The suspended sediment concentration (SSC) and particle size distribution (PSD) in the penstock of the study HPP are continuously measured using an innovative combination of several techniques. In this way, the variability of SSC and PSD is captured and the sediment load is reliably determined. Geometrical changes and material loss on the Pelton runners are quantified on the site based on repeated measurements on two buckets using structured-light 3D optical scanning. Efficiency changes are determined by 'sliding needle' index efficiency tests. In addition to these periodically performed tests, efficiency is also continuously monitored based on data time-series from the control system of the HPP.
In periods of high SSC and coarse particles in the turbine water, the costs of direct and consequential damages caused by the passage of sediment through the turbines may be higher than the revenues from the power sales. In such situations, it is economic to stop HPP operation for some time. Such shutdown of machines can only be practised if reliable sediment data are available in real-time. Therefore, this paper focuses on the measuring techniques to cope with hydro-abrasive erosion of turbines.

1. Introduction

Turbines of high- and medium-head run-of-river HPPs in the geologically young mountains of the Andes, the Himalayas and the Alps are particularly affected by hydro-abrasive erosion. The refurbishment and replacement of eroded turbine parts are economically relevant. Moreover, the geometrical degradation of the hydraulic profiles of runners, nozzles and guide vanes of Pelton und Francis turbines leads to reduced turbine efficiencies (e.g. [1]) and hence production losses. All in all, the profitability – and eventually the availability and safety – of such HPPs are negatively affected.

As a basis for adequate countermeasures in design, operation and maintenance of such HPPs, the knowledge on hydro-abrasive erosion and corresponding investigation methods need to be improved. Relevant quantities such as the sediment load, erosion depths, and efficiency changes have to be quantified using adequate measuring techniques. The IEC Standard 62364 [2] lists among others the governing parameters of hydro-abrasive erosion, defines the so-called particle load, and provides guidelines for the documentation and prevention of erosion damages. However, for HPP operators and consulting engineers it is not obvious how to tackle the problem in practice.

In an interdisciplinary on-going project initiated by VAW of ETH Zurich and Hochschule Luzern, the problem of hydro-abrasive erosion is investigated at the case study HPP Fieschertal, Switzerland [3]. This run-of-river HPP is located downstream of a major glacier and is operated by Gommerkraftwerke AG. The HPP is equipped with two horizontal axis Pelton units with nominal 515 m net head. Each unit has 32 MW nominal power, a design discharge of 7.5 m^3/s and two injectors. The runners have an external diameter of 2.80 m; the inner bucket width is 0.65 m. The injectors and the buckets are hard-coated. The goal of the on-going project is to contribute to a better understanding of the relations between suspended sediment load, turbine wear and efficiency losses as a basis for economic and operational optimization. Moreover, relevant measuring techniques are tested and further developed.

The schematic overview of the HPP Fieschertal with the monitoring program is shown in Figure 1. The suspended sediment load, turbine erosion and efficiency changes have been monitored since 2012. Figure 2 gives an overview on the runners in operation and the refurbishment works as well as the erosion and efficiency measurements performed until 2016 on each machine group (MG).

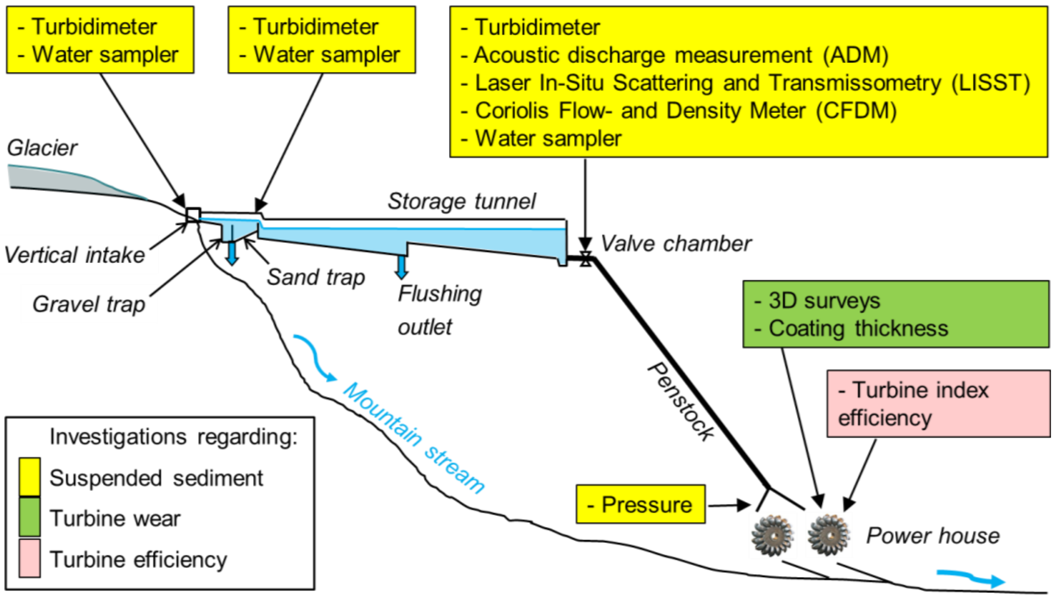

Figure 1: Schematic longitudinal profile of HPP Fieschertal with monitoring program (modified from [3, 4]).

In this paper, the measuring techniques used at the case study HPP Fieschertal for (i) suspended sediment monitoring (SSM), (ii) turbine erosion monitoring and (iii) turbine efficiency monitoring are described. Moreover, the benefit of a real-time SSM system for systematic HPP shutdowns in periods of particularly high erosion potential is demonstrated based on an example from a major flood event. Finally, the technical implications for measurements at HPPs equipped with other turbine types are discussed.

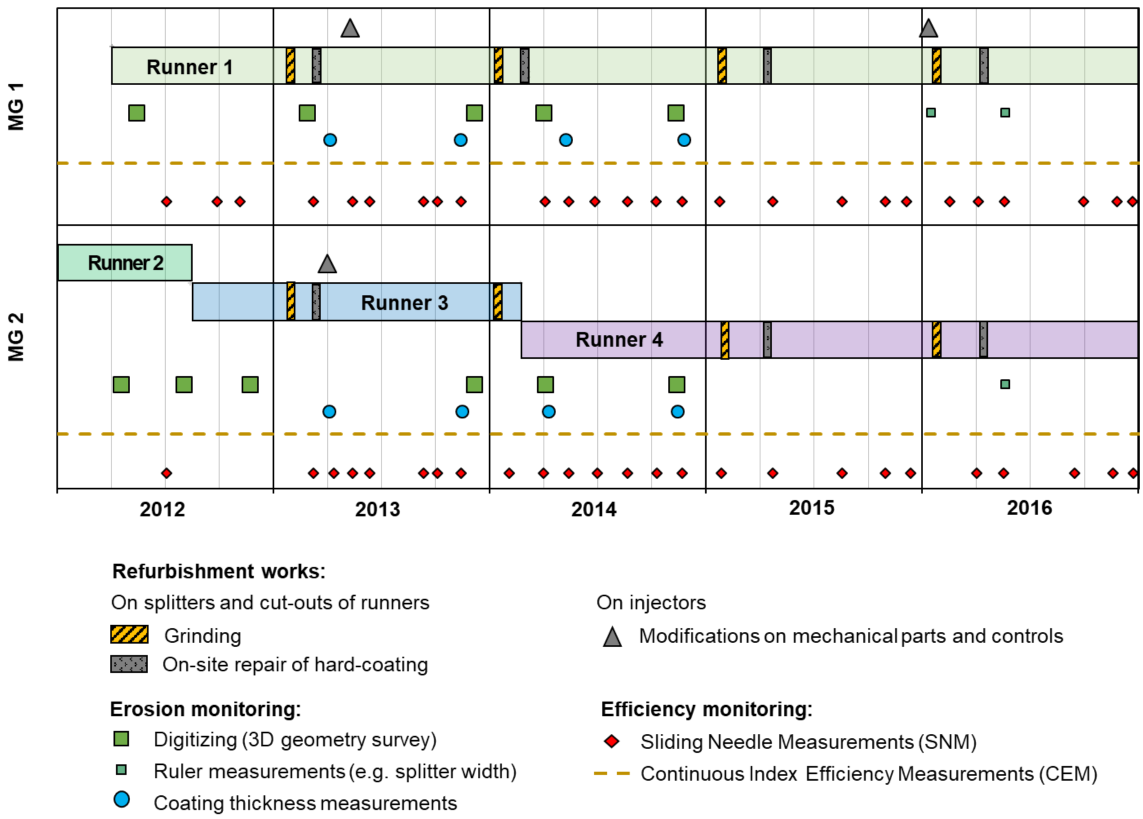

Figure 2: Schematic timeline showing the runners in operation, the refurbishment works as well as the erosion and efficiency measurements for both MGs in the HPP Fieschertal (extended from [3]).

2. Suspended sediment measurements

2.1 Gravimetric SSC

The SSC is defined as the mass of particles per volume of the water-sediment-mixture. The most reliable technique to determine SSC is by weighing of the dried residues in a laboratory (gravimetric method). Because the collection, transport and analysis of bottled water samples is quite an effort, indirect techniques for continuous SSC measurements have been developed over decades. A selection of such techniques, which are applied in HPP Fieschertal, will be described in the following section. Gravimetrically determined SSC are still required as a basis for the calibration of the indirect measuring techniques.

In the HPP Fieschertal, automatic water samplers (*Isco 3700* from Teledyne-Isco) are used to pump bottled water samples at least every ten days at three locations where staff is not permanently present (Fig. 1). Because high SSC – e.g. due to intense rain – are of particular importance, additional samples are pumped in such periods using trigger signals from the indirect SSC measuring techniques. The water samplers are controlled by an in-house software running on the local data acquisition PCs.

2.2 Indirect techniques for continuous SSC

In HPP Fieschertal, submersible *turbidimeters* (e.g. *CUS51D* from Endress+Hauser with air purge) are installed in the river at the intake and at the end of the sand trap (Fig. 1). In the valve chamber (Fig. 3), a turbidimeter model measuring at a free-falling jet (*AquaScat* from Sigrist Photometers) is installed on a sampling pipe fed from the penstock. Turbidity values are converted to SSC using a correlation based on gravimetrical SSC. If particle properties such as size, shape and color vary over time and independently of SSC, the SSC obtained from turbidimeters are temporarily biased.

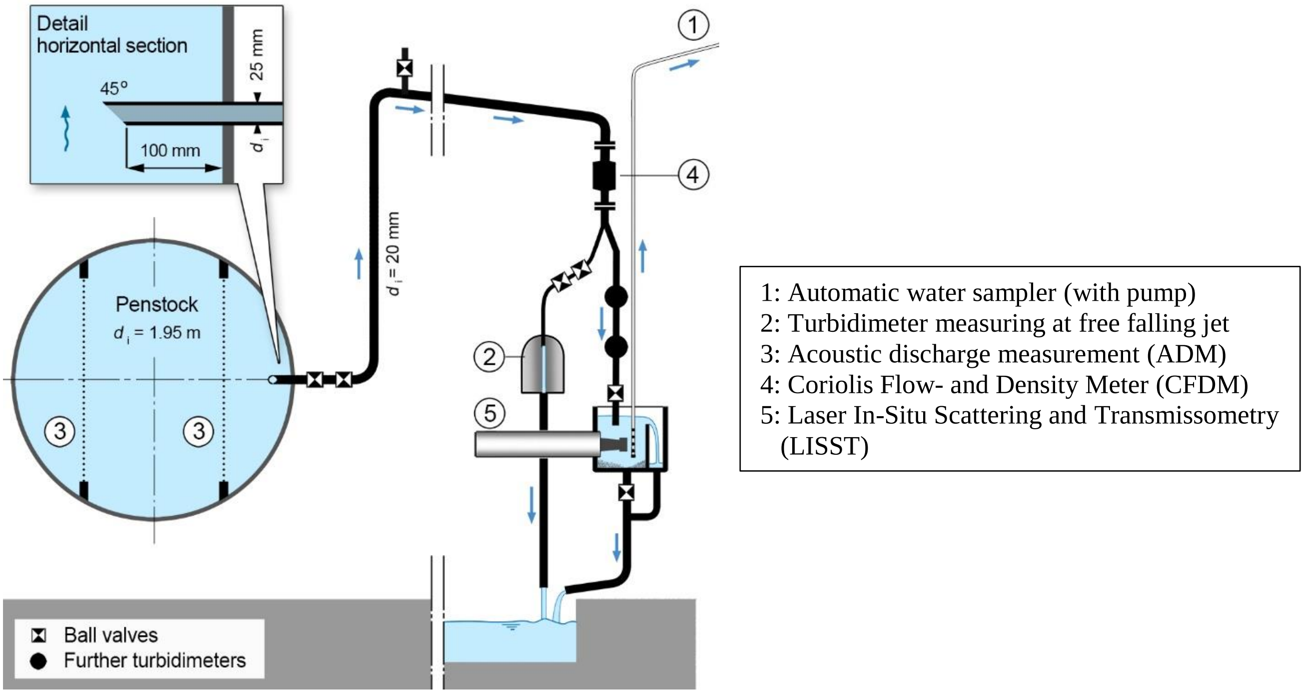

Figure 3: Set-up for SSM in the valve chamber (modified from [3]).

Acoustic (ultrasonic) signals are used for SSM in many ways. With single-frequency techniques and variable particle sizes, the SSC are temporarily biased (similar to turbidimeters). To overcome this limitation, multi-frequency acoustic backscatter instruments are under development. In HPP Fieschertal, a pre-existing acoustic discharge measuring (ADM) installation (*Risonic modular* from Rittmeyer, 1 MHz, 4 paths) is used for SSC measurements. By this way, SSC is measured directly in the penstock with a good spatial averaging and very low maintenance. In the present case, the SSC from the acoustic technique was found to be generally less sensitive to particle size variations than turbidimeters [3].

Laser In-Situ Scattering and Transmissometry (LISST) provides both SSC and detailed particle size distributions (PSD). As an advantage over turbidimeters and single-frequency acoustics, the prevailing PSD is considered in the SSC output from LISST. In HPP Fieschertal, a standard instrument without dilution mechanism (*LISST-100x* from Sequoia Scientific, with 90 % path reduction module) is installed at the end of the sampling pipe in the valve chamber (Fig. 3). With this instrument, the SSC measuring range is limited to a few g/l of the usually prevailing silt particles [3].

Moreover, a *Coriolis Flow- and Density meter* (CFDM) is installed on the sampling pipe in the valve chamber (Fig. 3). SSC is calculated from the measured mixture density and the average density of the particle material (2.73 t/m^3). In HPP Fieschertal, a *Promass 83* (DN15) from Endress+Hauser is installed. This instrument with its factory calibration is suitable to measure high SSC (e.g. > 5 g/l). With compensation of temperature effects and periodic field calibration, SSC with reasonable uncertainty (< 20 %) were obtained for > 1.5 g/l [3].

Finally, SSC is also monitored based on the *pressures* measured upstream of the turbines (Fig. 1) and other data from the control system of the HPP. Suspended sediment in the penstock leads to a higher pressure than that with clear water under the same operation conditions (headwater level and turbine discharges). In steady-state periods, SSC > 2 g/l were evaluated using this technique. As a drawback, this technique offers no pre-warning time because high SSC are only measured when a high sediment load is already in the penstock.

Using the described set of direct and indirect measuring techniques, SSC and PSD in the turbine water have been measured since 2012. The dried residues of selected samples were analyzed with respect to mineralogical composition, particle shapes and density. The SSC was on average 0.5 g/l and reached about 50 g/l in a major flood event (Fig. 9). The median particle size d_{50}, i.e. the diameter of particles not exceeded by 50 % of the particle mass was evaluated from the LISST data. The d_{50} varied between 10 µm (medium silt) and 100 µm (fine sand), quite independently of SSC. High SSC were measured in the wet season from mid-April to mid-October, i.e. the sediment transport season.

Figure 4 shows an example of the time series of (a) the characteristic particle sizes obtained from the LISST and (b) the SSC obtained from the various methods. When coarser-than-usual particles were transported, the turbidimeter and the single-frequency acoustic method underestimated SSC (as expected from theory). From the SSM data, annual sediment loads and particle loads according to IEC 62364 [2] were determined [3].

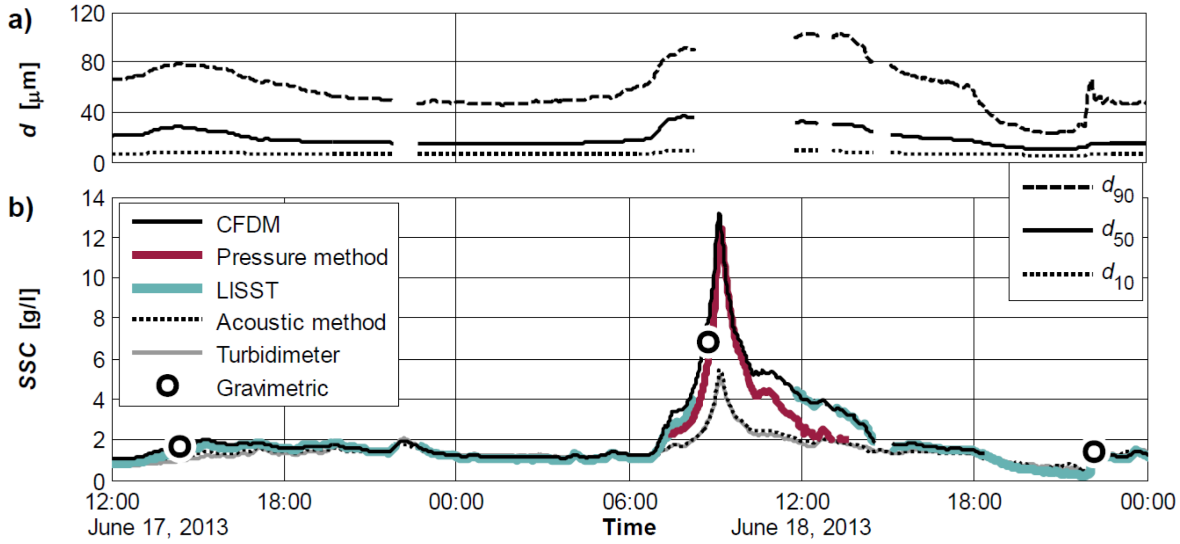

Figure 4: Time series of a) particle sizes obtained from LISST as well as of b) SSC from five techniques for continuous SSM and gravimetric reference SSC [4].

3. Turbine wear measurements

3.1 Overview

Hydro-abrasive erosion is measured on the turbine runners inside the turbine housings with (i) an optical 3D measuring system (section 3.2) and (ii) a thickness gauge (*Deltascope FMP 30* from Helmut Fischer) based on electromagnetic induction. The 3D surveys and the thickness measurements of the coating are usually performed before and after each sediment season. In some years, when 3D surveys were not included in the investigation program, geometrical quantities such as splitter widths and cut-out depths were measured with a ruler and templates. In addition, the damages on the buckets and needles are documented with photographs.

The results of the coating thickness measurements are described in detail in [3]. It was concluded that in absence of a major sediment transport event, the coating in the buckets lasted for several years. Most relevant for efficiency loss and the times between overhauls is the local erosion or the splintering of the hard-coating due to stone impacts at the cut-outs and splitters of the buckets. Such local erosion occurred also in years without major sediment transport events. The removal of the coating in these zones leads to pronounced erosion of the less resistant base material. Since the magnetic induction method is not suited for coating thickness measurements on the cut-outs edges and the splitter crests, and the erosion progressed into the base material, 3D surveys are conducted to quantify the erosion in these zones.

3.2 Digitizing (3D surveys)

The current geometries of two buckets per runner are repeatedly measured using an optical scanning sensor (*Comet L3D 5M* from Steinbichler, nowadays Carl Zeiss Optotechnik). This sensor, which works based on triangulation, has a resolution of five megapixels in a measurement volume of 480 x 400 x 250 mm. The distance between surface points is thus on average 190 µm. The specifications of the sensor were validated before every measuring campaign using a calibration template. Because the stainless steel buckets reflect light, a whitening spray is applied prior to scanning. Reference markers (Fig. 5) are used to improve the matching of point clouds and the measuring uncertainty. Due to the geometric conditions (line-of-sight obstructions by bucket parts and neighbouring buckets) and the relatively large size of the Pelton runners in the present case, about 75 shots from adequate angles are needed for one bucket (inner and outer sides). No measurements are possible in optically hidden erosion features such as narrow and sharp-edged grooves or undercut holes. The 3D survey of two buckets of one runner require about two on-site working days of a two-man team. One person works on the measurement laptop while the other adjusts the sensor position and the illumination. This measurement system is also used for the same purpose by [5].

Figure 5: Digitizing of Pelton bucket geometries inside a turbine housing in HPP Fieschertal: camera with projector mounted on a tripod with stick-on reference points on the buckets.

Figure 6 shows an overlay of the measured geometries of two digitized buckets before and after the sediment season 2012 in top view in the zone of the cut-outs. Erosion occurred mainly in the centre part of the cut-outs and on the tips of the splitters. On the outer sides of the cut-outs, where the jets do not interact with the buckets, the geometry was not altered with time. The perfect overlay in the zones without erosion indicates a good reproducibility of the geometrical measurements with this method. The reproducibility was estimated to be better than ±0.2 mm in the zones of the splitters and cut-outs. From the 3D models, alterations of the splitter cross sections and volume differences were analysed over time [3, 6].

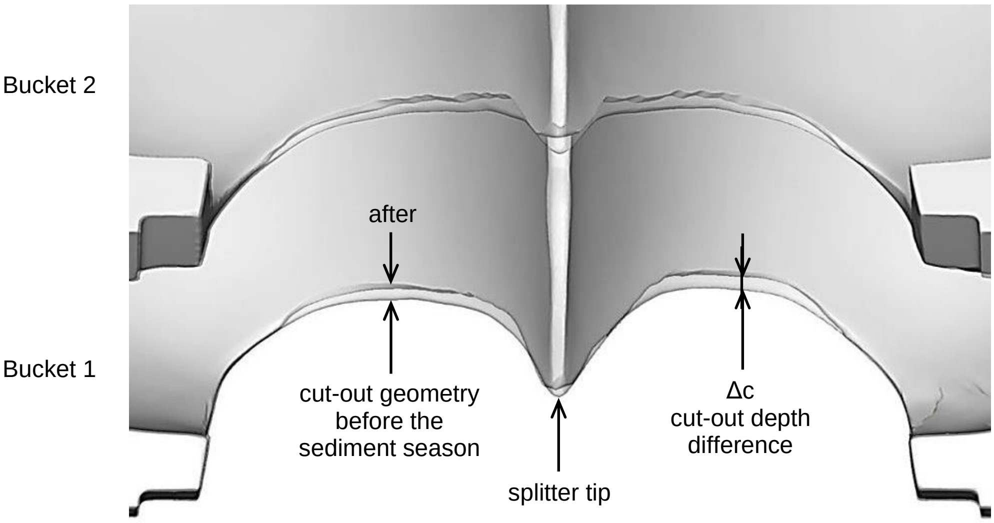

Figure 6: Overlay of the digitized geometries of the cut-outs and splitter tips before and after the sediment season 2012 for MG 2 [6].

4. Turbine index efficiency measurements

4.1 Sliding needle index efficiency measurements (SNM)

For turbine efficiency monitoring in the context of hydro-abrasive erosion it is not necessary to measure absolute efficiencies. Efficiency differences can be evaluated from index efficiency tests. A periodical determination of efficiency curves as a function of flow rate or power allows supervising the changes in efficiency. In the HPP Fieschertal the hydraulic head varies less than 1 % which facilitates such efficiency comparisons. In HPPs with high sediment loads, pressure taps have to be flushed on a regular basis. While this is less critical for head measurements, the measurements of an index flow rate based on pressure difference measurements, e.g. with a Venturi meter, becomes unfeasible in case of high sediment loads. Flow meters based on magnetic induction or acoustic meters based on transit time measurements (ADM) avoid such problems [6]. Their output signals are known to be well reproducible over time.

In HPP Fieschertal, index efficiency tests are performed by sliding needle measurements (SNM). Thereby both needles of one MG are opened continuously starting from a 40% opening – and after reaching full load – they are closed again continuously (Fig. 7). During a SNM only one MG is in operation. The test duration is approximately one hour to obtain quasi-steady state conditions. SNM can be performed in a much shorter time than a set of classical single point efficiency measurements. From the evaluated efficiency curve of each SNM (Fig. 7) a weighted efficiency is calculated. The time series of these values for each MG from 2012 to 2016 (as in Fig. 2) are shown in Figure 8 (filled markers connected with lines).

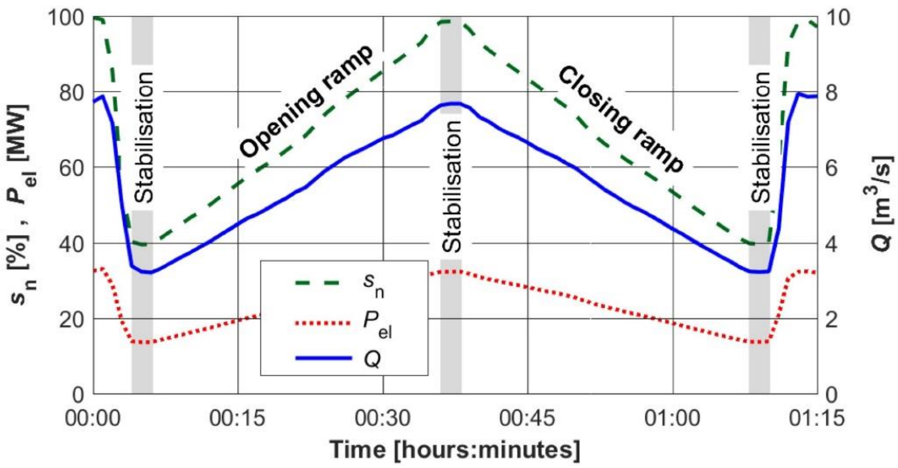

Figure 7: Time series of the needle strokes s_n, electric active power P_{el} and turbine discharge Q during a SNM (modified from [3]).

4.2 Continuous efficiency monitoring (CEM)

For an optimum operation of a HPP with more than one MG it is important to monitor the efficiency of each MG with good temporal resolution. Although the SNM interfere with the normal HPP operation for only one hour, such operation constraints are undesirable, especially for run-of-river HPPs in periods with full load operation, as during summer in the HPP Fieschertal. For this reason, a procedure was developed to enable continuous evaluation of turbine efficiency changes during normal operation.

For continuous monitoring, operation data from the control system of the HPP are recorded at 1 Hz, as for the SNM. For each data set (discharge, power output etc.) at a time step, efficiency is evaluated. The scatter of these efficiencies is unacceptably high. To reduce the scatter, a daily averaged difference to the reference curve from the last SNM is evaluated in steady state conditions. The scatter in the daily efficiency differences is further reduced by specially developed data processing, elimination of outliers and filtering. The time series of the daily efficiency differences with respect to the initial efficiency level are also displayed in Figure 8 for both MGs (empty markers). The daily efficiency differences still scatter more than those from SNM, but useful additional information on efficiency trends between the SNM is provided.

In HPP Fieschertal, an ADM (Endress + Hauser) is installed at the end of the penstock, upstream of the bifurcation to the two MGs. To measure the turbine discharges, Venturi sections were installed upstream of each turbine at their commissioning. However, with the silt-laden water and the present piping arrangement in HPP Fieschertal, the discharge signals from the Venturi sections are not reliable enough for efficiency monitoring. Therefore, if both MGs are running, the turbine discharges are calculated from the needle strokes and the respective needle curves (relations of needle strokes and turbine discharge recorded during SNM). The needle curves are subjected to changes due to hydro-abrasive erosion at the needles and the needle rings, as well as replacements of nozzle parts and modifications on the stroke sensors (triangles in Fig. 2). To compensate for these effects, the needle curves are always updated from the last SNM. This is one reason, why SNM are an important basis for CEM.

Furthermore, it was necessary to introduce plausibility tests to check the individual signals, especially of the pressure measurements. Pressure data are compared to calculated pressures from head water level measurements considering the head losses in the penstock as a function of the discharge.

In the second part of the sediment season 2012 an efficiency loss of 1 % was measured after 1902 operating hours at MG 1. The main cause for this efficiency loss is the major sediment transport event of July 2012 (Fig. 9). In the winter 2012 / 2013 the splitters and cut-outs were rounded by grinding (G in Fig. 8). This led to a measured increase in efficiency of 0.5 %. In the year 2014 the measured efficiency reduction of MG 1 was only 0.13 % after 3048 operating hours. Two further grinding and re-coating actions after the sediment seasons 2013 and 2014 led to smaller increases in efficiency. Efficiency benefits of on-site maintenance works depend on the erosion status of the runner.

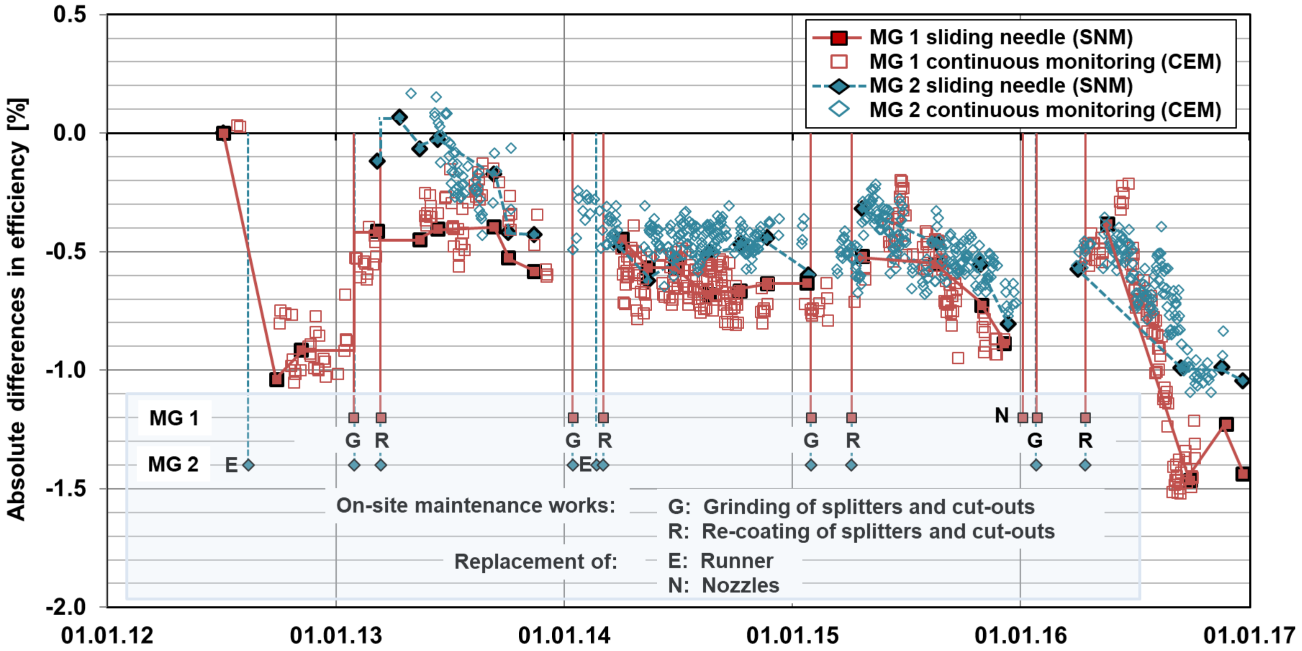

Figure 8: Efficiency history obtained from the SNM compared to the results of the CEM (needle stroke) with remarks on maintenance works and replacement of turbine parts (updated from [6]).

The efficiency difference over a sediment season was obtained as the mean difference between up to two SNM at the beginning and end of the sediment season, respectively. The efficiency differences over each sediment season are summarized in Table 1 for both MGs.

Table 1: Index efficiency differences over the sediment seasons and operating hours for each year.

Year	Operating hours		Absolute, weighted index efficiency difference [%]	
	MG 1	MG 2	MG 1	MG 2
2012	1902	-	– 0.97	-
2013	2096	3175	– 0.13	– 0.43
2014	3076	3126	– 0.13	+ 0.03
2015	2629	4020	– 0.29	– 0.36
2016	2826	3450	– 0.95	– 0.44

From the evaluated data, it was concluded that efficiency differences do not correlate well with the operating hours nor the annual sediment loads, because the efficiency differences also depend on the condition of the runner (erosion and refurbishment status before the exposure period), single sediment transport events and the onset of base material erosion [6]. Because efficiency differences are hardly predictable, it is recommended to perform continuous long-term monitoring. An efficiency history as in Figure 8 is currently not found in literature and provides a valuable basis for planning of refurbishment works and economic considerations for optimized HPP management.

5. Use of SSM system to prevent excessive turbine erosion

In some rather short periods of the year, the SSC in the turbine water is particularly high and coarser particles are transported. This leads to an increased erosion rate and hence higher specific production costs. If the direct and consequential costs caused by the sediment passage through the turbines is higher than the revenues from the power sales, it is economic to close the intake and to pause the HPP operation for some time. Of course, this option depends on production obligations and the possibilities to compensate HPP outages. Technically, a reliable SSM system providing alerts with sufficient pre-warning time is required. At the HPP Fieschertal, a shutdown of 16 hours during the major flood in 2012 (Fig. 9) would have led to a benefit of about 200 000 EUR, corresponding to almost 3 % of the annual nominal revenue of the HPP [7].

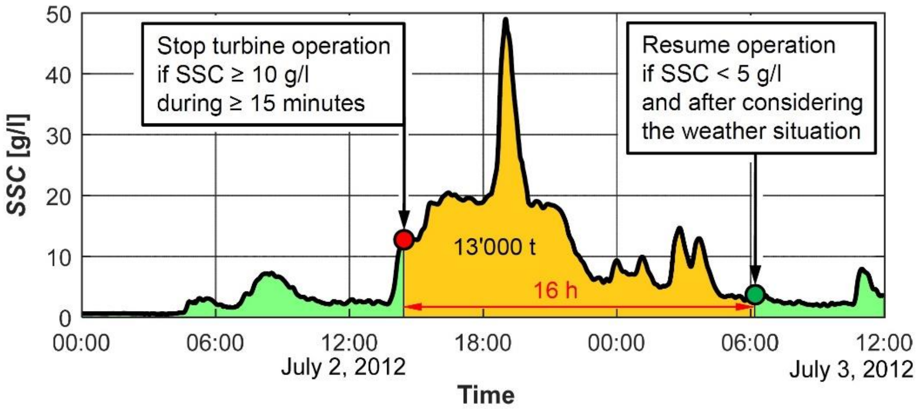

Figure 9: Measured SSC time series in the turbine water of HPP Fieschertal during a major flood event with proposed shutdown scenario [7].

5. Considerations for other turbine types

The SSM techniques treated in Section 2 are applicable for various HPPs regardless of the turbine type. The selection of a suitable combination of SSM techniques depends mainly on the expected SSC and PSD ranges, the required reliability, site access, possibilities for sample and data transfer, available staff and budget. Depending on the measuring locations (river, intake, sand trap, valve camber, upstream of turbines, or tailwater channels), pressure reduction and de-aeration facilities may be required on water sampling pipes.

With respect to erosion measurements (Section 3), the effort is much higher for Francis than for Pelton turbines. Whereas Pelton runners are quite easily accessible above the tailwater level, Francis turbines need to be sealed on the up- and downstream sides, dewatered and possibly partly dismantled for the inspection of runner blades, guide vanes, facing plates, labyrinth seals, etc., depending on their size and layout. For large vertical-axis Pelton turbines, the effort for erosion measurements is generally higher than for smaller or horizontal-axis Pelton turbines because more scaffolding is required to access large runners from below. During the installation and replacement of turbine parts of any turbine type, it is recommended to measure the masses of the components using a crane scale, in order to determine the mass losses during operation.

With respect to the measurement of efficiency differences (Section 4), there are no fundamental differences between Pelton and Francis turbines. Periodic index efficiency measurements can be performed by the sliding needle and the sliding gate methods [8], respectively. The described method for CEM is similarly applicable for other turbine types.

6. Conclusion and Outlook

Well-known and newly applied measuring techniques for (i) suspended sediment, (ii) turbine erosion and (iii) efficiency changes were reviewed and presented by exemplary results from a field study at a high-head HPP in the Swiss Alps. The main findings include:

i) For SSM, a combination of several techniques is required to cover the wide SSC range of interest and to capture PSD variations. Such a combined instrumentation is recommended because it allows to determine the suspended sediment and the particle loads according to IEC 62364 [2] with reasonably low uncertainty. A system for continuous SSM is useful to issue warnings for temporary HPP shutdowns to prevent disproportionate erosion damage.

ii) Repeated 3D surveys allow quantifying the erosion on Pelton buckets in detail, particularly on the splitter crests and cut-out edges which are particularly relevant for the turbine efficiency. The measuring uncertainty in these zones was estimated as ±0.2 mm. From the 3D models, sections and volume differences can be analysed.

iii) The SNM allow evaluation of efficiency differences (repeatability in the order of ±0.2 %) with relatively low effort for the HPP operator. The CEM has higher scatter but also higher temporal resolution. Both methods complement each other. Long-term efficiency monitoring is recommended because efficiency degradations do not well correlate with operating hours nor annual sediment loads.

In the continuation of the research project at HPP Fieschertal, further instruments will be tested and additional data will be evaluated. It is recommended to perform similar studies at other HPPs with Pelton or Francis turbines on sediment-rich rivers to extend the knowledge and experience to better cope with turbine erosion and its consequences.

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References

[1] Cateni A, Magri L, Grego G, "Optimization of Hydro Power Plants Performance – Importance of rehabilitation and maintenance in particular for the runner profiles", *Proc.* 7th Intl. Conf. on Hydraulic Efficiency Measurements (IGHEM), Milan, Italy, 2008.

[2] IEC 62364, "Hydraulic machines - Guide for dealing with hydro-abrasive erosion in Kaplan, Francis and Pelton turbines", Edition 1.0, *International Electrotechnical Commission*, Geneva, Switzerland, 2013.

[3] Felix D, "Experimental investigation on suspended sediment, hydro-abrasive erosion and efficiency reductions of coated Pelton turbines", *VAW-Mitteilung* 238 (R. M. Boes, ed.), and *PhD thesis* 24145, ETH Zürich, Switzerland, 2017.

[4] Felix D, Albayrak I, Abgottspon A, Boes R M, "Real-time measurements of suspended sediment concentration and particle size using five techniques", *Proc.* 28th IAHR Symposium on Hydraulic Machinery and Systems, Grenoble, France. *IOP Conf. Series: Earth Environ. Sci.* **49**, 122006, 2016.

[5] Rai A K, Kumar A, Staubli T, "Hydro-abrasive erosion in Pelton buckets: Classification and field study". *Wear* **392–393**, 8–20, 2017.

[6] Abgottspon A, Staubli T, Felix D, "Erosion of Pelton buckets and changes in turbine efficiency measured in the HPP Fieschertal", *Proc.* 28th IAHR Symposium on Hydraulic Machinery and Systems, Grenoble, France, *IOP Conf. Series: Earth Environ. Sci.* **49**, 122008, 2016.

[7] Felix D, Albayrak I, Abgottspon A, Boes R M, "Optimization of hydropower plants with respect to fine sediment focusing on turbine switch-offs during floods", *Proc.* 28th IAHR Symposium on Hydraulic Machinery and Systems, Grenoble, France. *IOP Conf. Series: Earth Environ. Sci.* **49**, 122011, 2016.

[8] Abgottspon A, Staubli T, "Index Tests of a Francis Unit using the Sliding Gate Method", *Proc.* 7th Intl. Conf. on Hydraulic Efficiency Measurements (IGHEM), Milan, Italy, 2008.