Abstract: Considerable hydro-abrasive wear may occur at turbines of hydroelectric power plants particularly at high-head run-of-river schemes in glaciated catchment areas. In order to optimize the operation of such power plants, real-time information on suspended sediment is required. Optical and acoustic devices for suspended sediment monitoring were calibrated in the laboratory and installed at a case study site in the Swiss Alps, delivering first results. Furthermore, the 3D-geometry of the turbine buckets was digitalized with high accuracy to quantify changes in geometry and material loss.

1 Introduction

Hydro-abrasive wear at turbines and steel hydraulics parts due to suspended mineral particles in the water can lead to substantial maintenance costs and significant negative impacts on power generation and revenue at hydroelectric power plants (HPP), particularly at high-head run-of-river type plants in glaciated catchment areas with igneous rocks such as granite. For well-balanced plant design and operation there is still a need for improved design knowledge and adequate real-time measuring systems to monitor suspended sediment load at prototype conditions [1]. In order to advance in the understanding and addressing of this problem VAW of ETH Zurich initiated an interdisciplinary project in cooperation with Hochschule Luzern and supported by swisselectric research, the Swiss Federal Office of Energy, the power plant operator (Gommekraftwerke) and co-owner (Bernische Kraftwerke) as well as industry partners (Andritz Hydro and Rittmeyer). This project focusses on the investigation of hydro-abrasive wear at the existing high-head HPP Fieschertal, in Upper Valais, Switzerland. Since the plant was built in 1976 severe hydro-abrasive wear 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. Increased yield of fine sediment is expected in the Alps due to the glacier retreat.

In this project, suspended sediment in the turbine water is continuously monitored during two or three summer seasons using various measuring techniques. In parallel material loss on turbines and efficiency reduction are measured. Suspended sediment load, material loss on turbines and efficiency reduction shall be correlated in order to verify and improve forecasting of hydro-abrasive wear.
This paper focuses on suspended sediment monitoring (preliminary laboratory tests and first case study results) and the selected method for quantifying geometry changes at turbine runners.

2 Suspended sediment monitoring techniques

2.1 Overview

For the investigation of hyro-abrasive wear the following parameters are of interest:

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

Hardness and shape of the particles are assumed to be relatively constant and can be determined by laboratory analysis of a few periodically taken samples. SSC and PSD however may vary considerably in time. Thus a continuous monitoring of these parameters is required. Various devices to monitor SSC are currently available or under development. The following optical and acoustic devices were selected for this study:

(a) Turbidimeters (attenuation and/or scattering of near infrared or laser light),
(b) Portable laser transmissiometry and diffraction (LD) and
(c) Acoustic transducers as used in acoustic discharge measurement (ADM) devices.

From literature (e.g. [2]) it is known that the particle size has a significant effect on hydro-abrasive wear. As to our knowledge the portable laser diffraction device is the only instrument that provides in-situ real-time particles size distributions in addition to information on SSC.

2.2 Turbidimeters

For monitoring of suspensions in industrial processes, water and wastewater plants optical probes - called “turbidimeters” - are used. The readings (displayed in optical units) delivered by such probes are converted to SSC using a calibration curve which has to be obtained by the user for the prevailing type of particles. The devices listed in Tab. 1 were tested in the lab prior to the installation at the case study site.

<table>
<thead>
<tr>
<th>Product</th>
<th>Manufacturer</th>
<th>Measuring principle</th>
<th>Installation</th>
<th>Nom. range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solitax ts-line sc</td>
<td>Hach-Lange</td>
<td>Combined scattering at 90° and 140°</td>
<td>submerged</td>
<td>0...4000</td>
</tr>
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<td></td>
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<td>[FNU]</td>
</tr>
<tr>
<td>Turbimax W CUS41</td>
<td>Endress-Hauser</td>
<td>Scattering at 90° multiple channels</td>
<td>submerged</td>
<td>0...9999</td>
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<td>[FNU]</td>
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<tr>
<td>TurbiScat</td>
<td>Sigrist Photometer</td>
<td>Scattering at 90° and 25°, in combination with transmission</td>
<td>in-line (pressure flow)</td>
<td>2 channels</td>
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<td></td>
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<td>0...4000</td>
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<td>[FNU]</td>
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<tr>
<td>AquaScat</td>
<td>Sigrist Photometer</td>
<td>Scattering at 90°</td>
<td>in-line (free falling jet)</td>
<td>0...4000</td>
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<td>[FNU]</td>
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<tr>
<td>TF16-N with flow cell F20</td>
<td>Optek Danulat</td>
<td>Transmission (0°)</td>
<td>in-line (pressure flow)</td>
<td>0...5</td>
</tr>
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<td>[CU]</td>
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</table>
2.3 Portable laser transmissiometry and diffraction (LD)

Among the available portable laser diffraction devices a LISST-100X, Typ C (from Sequoia Scientific) was selected. This submersible instrument can also be used for investigations of suspended sediment in reservoirs and desilting facilities. A similar LD instrument is in use at a high-head HPP on a mountain stream in Austria [3]. The use of LD instruments at HPPs is discussed in [4]. By means of a mathematical inversion of the measured laser intensities the volume concentrations of 32 log-spaced particle size bins are calculated. The total mass concentration (SSC) can be calculated using an estimated sediment density. The nominal size range of measurable particles is 2.5 to 500 micrometers for the selected type of instrument. In order to extend the range of measurable SSC the optical path length was reduced from 50 mm to 5 mm by using a 90%-path reduction module.

2.4 Acoustic measurements at ADM-installations

In many HPPs worldwide discharges are measured using the acoustic transit time method (acoustic discharge measurement ADM). Ultrasonic pulses are subsequently sent through the flow on several paths, which are arranged oblique to the main flow direction. Between two identical transducers that are installed at the penstock or channel walls ultrasonic pulses are sent and received once forward and then backwards. From the difference in the measured “time of flight” between both directions the average flow velocity and discharge are calculated. Acoustic discharge measurement can be influenced or possibly disrupted in case of high SSCs [5]. On the other hand, the alteration of the received signals due to the presence of mineral particles can be used for (at least qualitative) suspended sediment monitoring.

3 Laboratory investigation on suspended sediment monitoring

3.1 Experimental set-up and methodology

Prior to the field study the devices for suspended sediment monitoring were tested in the hydraulic laboratory of Hochschule Luzern, at an existing facility of the Competence Centre for Fluid Mechanics and Hydro Machines [6]. In a tank equipped with a stirrer (Fig. 1) various suspensions of water and mineral particles with SSC from 0.1 g/l up to 50 g/l (depending on the type of particles) were prepared. Starting from a zero measurement in drinking water the concentration was increased step-wise and measurements were done simultaneously with all devices involved. All devices were placed at the same level.

Fig. 1: Mixing tank in the hydraulic laboratory with optical and acoustic devices for measuring suspended sediment, left plan view and right vertical section.
3.2 Materials

According to previous investigations [6] the suspended sediment at the case study site consists of approximately 20% quartz, 50% feldspar and 30% mica, i.e. the main components of granite rock. The mineral particles used in the laboratory tests were selected considering the similarity to natural conditions at the case study site. Most of the particles were bought from industrial applications. In addition, natural particles taken from the turbine’s tailwater channel during revision works (deposit in the pump sump of the turbine cooling system) were included in the tests. Glass beads were used as a reference (spherical shape). Quartz and feldspar powder particles have angular shape (from grinding) while quartz fine sand and mica powder have rounded (natural sand) and flaky shape, respectively.

3.3 Results

First results of the measurements made with a turbidimeter, the LISST and the acoustic method are presented in this section. The measured values (except for PSD) are plotted against the reference SSC, which was determined by samples taken from the tank at the instrument’s elevation (three samples per concentration level). By weighing the samples before and after drying in the oven, the effectively prevailing SSC was determined, deducting the dissolved minerals from the residue. Reference measurements of PSD were obtained from the samples analysed by a non-portable laser diffractometer (Horiba) at the Geotechnical Institute of ETH Zurich.

Fig. 2 shows turbidity measured by the optical transmission probe (Optek) as a function of the reference SSC for four kinds of particles and d50, which is the particle diameter of 50% finer, according to the PSD reference measurement. The plotted values are averages of 500 measurements per concentration level, recorded at 1 Hz.

In the displayed range of SSC there is a linear relationship between turbidity and the reference SSC for each type of particle. However, turbidity is not only function of SCC but also of particle type with effects of particle size, shape and optical properties.
Fig. 3 shows the damping of the amplitude of the received ultrasonic pulses (forward scattering) normalized with the amplitude measured in drinking water (SSC = 0) as a function of the reference concentration for various kind of particles in the mixing tank. The amplitudes were measured at a distance of 1.73 m away from the sender and the sent pulses have a frequency of 1 MHz. The plotted values are averages over 60 values per concentration level, recorded at 1 Hz. The amplitude of the received signal decreases almost linearly as SSC increases. The damping depends on particle material, size and shape. Previous investigations [6] indicate that the calibration curves for the acoustic method vary less with particle size than those of turbidimeters.

Fig. 3: Relative amplitude of received ultrasonic pulses as a function of reference SSC

Fig. 4 shows a comparison of the time-averaged PSDs measured by LISST at 1Hz for 100s at a nominal SSC of 1 g/l and the reference PSDs for feldspar and quartz fine sand. In LISST PSD calculations, particle shape was assumed to be “irregular”. The PSDs measured by LISST match approximately with the reference PSDs, e.g. with respect to the range of d_{50} and the general shape of the PSD (narrow or wide distribution), for fine sand as well as coarse silt. The PSD of feldspar powder, whose left end touches the lower limit of measureable sizes, is biased by “fine out of range particles” [7]. The LISST underestimates the proportion of coarser particles within the PSDs; this is more pronounced for fine quartz sand. It should be noted that for the flaky shape of mica powder the definition of the particle diameter is not obvious and it was not possible to check the accuracy of the reference PSDs, since in contrast to SSC no primary measuring method is available. The deviations between LISST and the reference measurements will be further analyzed.

The relationship between the SSC measured by LISST and the reference SSC is presented in Fig. 5. Plotted values are again the time-averages of 100 measurements per concentration level at 1 Hz. For the conversion of volume concentration to mass concentration (SSC) a density of 2.65 kg/l (standard value for quartz) was assumed for all materials, leading to an error of presumably less than 5%.
For fine quartz sand, which is the coarsest particle among the other particles, SSC measured by LISST correspond generally well to the expected SSCs (1:1-line). It should be noted that no custom calibration was applied. For feldspar powder, the LISST SSCs correspond to the reference SSCs at lower concentrations, but LISST increasingly overestimates SSCs at higher concentrations. This can be related to the effect of “fine out of range particles”, which may bias the inversion and becomes more pronounced as the SSC approaches the upper measurement limit of the LISST. For the mica powder however, the LISST significantly overestimates the SSC (factor of 6), what can be attributed to the flaky shape of these particles producing over-proportional scattering.

Fig. 4: PSDs measured in by portable laser diffraction (LISST) and by the reference method

Fig. 4: SSCs determined by LISST as a function of reference SSC
4 Field investigations on suspended sediment and turbine wear

4.1 Installation of suspended sediment monitoring devices

After the tests were completed in the laboratory, the devices for real-time monitoring of suspended sediment were installed in the HPP of Fieschertal (see Fig. 6). Most devices were placed in the valve chamber at the top of the penstock and fed by a sampling pipe with sediment-laden water taken from the axis of the penstock. In addition, two turbidimeters were installed and turbined water is pumped up to them from each turbine unit’s tailrace channel. An automatic water sampler with 24 bottles in the valve chamber was installed to collect samples of the turbined sediment-laden water. SSC is determined from the water samples and used to calibrate the instruments with respect to the particles of the study site. The water sampler is triggered by a turbidimeter in order to take more samples during sediment peaks.

4.2 First results on suspended sediment monitoring

On July 2 and 3, 2012, a major thunderstorm occurred in Fieschertal, which produced a flood discharge with an estimated return period between 10 and 30 years. Fig. 7 shows the time series of turbidity measured by optical transmission (Optek) and the scaled relative amplitude of the received ultrasonic pulses at one path of the acoustic discharge measurement installation. The scaled relative amplitude of the received ultrasonic pulses is well in line with the turbidity time series, except for the highest peak that was only recorded by optical transmission. This means that the sampling pipe was not clogged during the event and that at least qualitative information on suspended sediment, measured directly in the power waterway, can be retrieved from ADM-systems existing in many HPPs. The results are promising to develop a method to estimate real-time SCC using the amplitude of received acoustic signals available as an auxiliary parameter in ADM-systems.
Since the prevailing particles in Fieschertal consist of mostly feldspar and mica particles and the calibration curves of the optical transmission probe for powders of these materials are similar (Fig. 2), the calibration curve of feldspar powder was used to estimate the SSC. Based on the assumption, that the suspended sediment during the thunderstorm was similar to the feldspar and mica particles used in the laboratory, the turbidity peak of almost 5 CU (Fig. 6) corresponds to approximately 20 g/l, what is relatively high. Water samples taken during the thunderstorm will be analysed to obtain more precise SSCs by weighing of dried samples.

Besides sediment peaks due to weather phenomena, there are sediment peaks which depend on the power plant’s operation and on the hydraulic conditions in the free surface tunnel, which serves as a daily storage reservoir. Low water levels in the free surface tunnel may cause re-suspension of settled particles and may thus lead to relatively high SSCs [6].

4.3 Turbine inspections and 3D-digitalization of bucket geometry

Besides monitoring of suspended sediment the turbines are inspected in the ongoing project at least before and after the sediment season and occasionally during the sediment season, e.g. during flushing of the free surface tunnel. The local coating thicknesses in selected buckets are measured with a thickness meter based on magnetic induction.

Erosion damages on the turbine buckets are documented with photographs and their current geometries are measured with an optical scanner (Fig. 7). The working principle of the optical scanner is based triangulation and 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. The optical measurements focus on the monitoring of the abrasion of the main splitter in selected buckets.
Fig. 7: Digitizing of Pelton buckets geometry in the power plant: Special camera mounted on a tripod below the buckets of the runner with stick-on reference points.

Fig. 8 shows the results of the geometric analysis. The mid-plane cut through the bucket in the axis of the main splitter is displayed with a solid black line. This cut is extracted from the point cloud of the 3D-digitization of bucket no. 1. The initial (theoretical) splitter profile is shown as a dotted black line. A serious abrasion of the main splitter can be observed from the difference of the two splitter contours. The grey lines with the vertical axis on the right hand side show the abrasion (in mm) at the top of the main splitters of two digitized buckets. The abrasion processes on both splitters are comparable with respect to the affected parts of the splitters and the magnitude of the abrasion depth of approximately 8 mm. Further scans after the sediment season will allow to obtain quantitative data on geometry changes and to relate the material loss to the suspended sediment load. The second turbine inspection made in August 2012 after the thunderstorm described above revealed considerable wear on the runners of both turbines.
5 Conclusions

Regarding suspended sediment monitoring, various devices were investigated in the laboratory to assess the measuring range, measuring uncertainty and calibration parameters. Custom calibrations depending on the type of particles prevailing in the turbine water are required for turbidimeters and the acoustic method. As a drawback, temporal variation of the properties of the prevailing suspended sediment particles may lead to significant uncertainty when estimating SSC from turbidimeters or acoustic signals obtained from sensors used in ADMs.

First results show that LISST allows capturing PSDs and SSCs for particles in the range of silt to fine sand at concentrations up to a few g/l. Existence of particles smaller than the lower limit of the measurement range of the LISST may bias PSD and thus cause an overestimation of SSC. First results further indicate that coarser fractions within the PSDs are underestimated by the LISST. Concerning the particle shape effect, mica in suspended sediment may lead to a considerable overestimation of SSC. This is related to the fact that the flaky shape of mica differs greatly from the rounded or angular shape of the other investigated particles and from the currently assumed particle shape in the calculation model.

First evaluation of field data showed that during a major thunderstorm two devices (optical transmission probe and ADM) were able to record the time series on turbidity and amplitude, respectively. The good correlation between acoustic amplitude damping and optical transmission is promising to develop a real-time suspended sediment monitoring based on ADM devices. Devices for suspended sediment monitoring based on optical methods are suitable at lower concentrations while the use of ADM signals is advantageous at higher concentrations.
Regarding monitoring of turbine wear, digitalization of the 3D-geometry of Pelton buckets by the means of an optical scanner offers the possibility to quantify geometry changes and thus material loss at turbine runners.

6 Outlook

The data from the laboratory measurements and the field will be further evaluated. The combination of acoustic and optical methods and the use of existing ADM-devices will be pursued. After the first sediment season the data from the turbine inspections and turbine efficiency measurements will be evaluated. In view of the damages observed on the turbine runners after the thunderstorm, the option of temporary turbine shutdowns for some hours during extreme sediment peaks shall be further investigated towards the determination of economically balanced switch-off criteria based on SSC and possibly particle size.

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