Suspended sediment concentrations and turbine wear during the drawdown of two Alpine reservoirs

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1. Introduction

Reservoir sedimentation is nowadays one of the main concerns in the operational management of dams. Despite its long-term process, it had an increasing significance in the last decades. The decrease of the reservoir capacity due to sedimentation has impacts on the reservoir’s main purpose such as hydropower production, flood protection and drinking and irrigation water availability (e.g. Müller 2012).

If the sediment deposits reach the intake of a hydropower plant (HPP), the operation efficiency and safety of the hydraulic scheme are threatened. A sustainable management of both the reservoir and the HPP requires an adequate sedimentation monitoring and control.

Adaptive strategies such as dam or intake heightening can be used to cope with reservoir sedimentation. However, the most efficient and sustainable solutions must guarantee the balance of sediments between the head- and tailwater of the dam. In this case, sediment routing, sluicing and/or venting techniques may be used. These may consist of opening outlet gates, resulting in considerable water losses, or releasing a water-sediment mixture via the headrace tunnel and the turbines. In the present paper, this last option is explored.

Conveying sediment-laden water through the turbines may expose the machinery steel parts to the so-called hydro-abrasive wear or erosion. This process has demonstrated to influence the turbine geometry and efficiency, leading to significant costs and downtime of turbines with corresponding production losses (Abgottspon et al. 2013). At low reservoir water levels, the hydro-abrasive potential is enhanced by the higher suspended sediment concentration and size of the particles due to resuspension of previously settled sediments (e.g. Felix et al. 2014).

Recently, the suspended sediment characteristics during the drawdown of two reservoirs – Gepatsch (Kaunertal HPP, Austria) and Räterichsboden (Handeck 2 HPP, Switzerland) – were monitored and the measured data were analyzed. In both cases, a considerable part of the sediment-laden water was released through the turbines, which allowed the evaluation of the effects of the sediments on the turbine wear.

The Kaunertal HPP was built between 1961 and 1964 by TIWAG-Tiroler Wasserkraft AG in the western part of Tyrol at the confluence of the Faggenbach with the River Inn (Tschada and Hofer 1990). It is equipped with 5 Twin-Pelton turbines with 2 nozzles and 23 buckets for each runner and uses a head of up to 895 m between the Gepatsch reservoir and the Inn River to generate a maximum output of 390 MW. The design discharge is 48 m$^3$/s and the mean annual production of the HPP is about 661 GWh.

Handeck 2 HPP is an underground plant built between 1947 and 1950 by Kraftwerke Oberhasli AG (KWO). It is equipped with 4 Pelton turbines with vertical axis, having 2 nozzles and 22 buckets each. A total head of 463 m and a discharge of 32 m$^3$/s from the Räterichsboden reservoir result in a maximum output of 136 MW and an installed capacity of 136 MW.

The monitoring periods were from the 8/12/2015 to 14/01/2016 for Kaunertal HPP and from 19/01/2016 to 05/02/2016 for Handeck 2 HPP. During these periods the water levels of the Gepatsch reservoir and the Räterichsboden reservoir
were lowered within a week or so and then kept at a low level by running one turbine at each HPP. At the HPP Kaunertal the damage was concentrated on one Pelton runner by using mainly one part of a Twin-turbine. Both HPPs are equipped with Pelton turbines. As the geometry of their buckets may change due to hydro-abrasive erosion, turbine inspections were conducted in both cases by means of a 3d-scan. The inspections and scans were performed at least at the beginning and end of the monitoring period.

The results comprising suspended sediment characteristics and their effects on the turbines are presented for both study sites, and the main conclusions are drawn.

2. Experimental setup, equipment and procedures

2.1 Sediment monitoring

Regarding the abrasion potential of suspended sediments, the following parameters should be taken into consideration (see e.g. Duan and Karelin 2002, Felix et al. 2016a):

- suspended sediment concentration (SSC);
- particle size distribution (PSD);
- particle shape;
- mineralogical composition and particle hardness (typically on Mohs’ scale), and
- particle solid density.

The particle shape can be evaluated from microscope images of dried particles and the particle hardness can be determined based on tables and quantitative mineralogical analysis using Rietveld-X-ray diffraction. The solid density of the particles can be measured in the laboratory with a pycnometer.

In the present work, particle shape, mineralogical composition and particle density were obtained by these methods based on sediment samples taken as representative for the whole monitoring period. The analyses were performed by the Institute for Geotechnical Engineering (IGT) and by the Institute for Building Materials (IfB) at ETH Zurich, respectively.

The parameters SSC and PSD, however, can be subject to strong and quick temporal variations and hence were monitored with higher temporal resolution.

In the present monitoring campaigns, the equipment for the sediment monitoring comprised an automatic water sampler (bottle samples), turbidimeters and a Coriolis Flow- and Density-Meter (CFDM). Bottle samples are the basis for all SSC measurements. The SSCs of the bottle samples were determined in the laboratory by the gravimetric method, i.e. by weighing of the dried residues. An automatic water sampler was installed to take samples of sediment-laden water (e.g. Felix et al. 2016b).

For continuous SSC monitoring the use of turbidimeters is quite common. A conversion function from turbidity to SSC has to be established by comparing the gravimetrically determined SSCs of occasionally taken bottle samples and the turbidimeter readings at corresponding times. As the turbidity depends on PSD, shape and colour of the particles (e.g. Downing 2006, Boes et al. 2013), the SSC values inferred by this method may be biased if these properties change. Another drawback is fouling of the optics in long term use. This can be overcome by automatic cleaning (wiper or pressurized air).

A Coriolis Flow- and Density-Meter (CFDM) was another technique used to evaluate the SSC from the density of the sediment-laden water. This device measures the mass flow, i.e. the mass per unit time (e.g. kg/s), and the mixture density, $\rho_{\text{mix}}$ of the sediment-laden water flowing through the device. This device is particularly useful at high SSCs which are most relevant for turbine abrasion. Bishwakarma and Støle (2008) and Felix et al. (2016b) showed that this technique can be used to determine SSC of sediment-laden water in power waterways. SSC is calculated from the measured mixture density and the densities of clear water and the particles, respectively. The water temperature is also measured and used to calculate the clear water density.
The monitoring setups installed in the Kaunertal and Handeck 2 HPPs are shown in the Figure 1.

![Figure 1 – Experimental setup (a) in Kaunertal HPP and (b) in Handeck 2 HPP (*LISST measurements are not presented).](image)

At Kaunertal HPP, a sampling pipe collects the water from an outlet of the penstock right upstream from the turbine. To reduce the pressure from almost 90 bars to ambient pressure an orifice with an inner diameter of 1.2 mm was installed. Due to the abrasive wear, resulting in an increasing discharge through the orifice, it had to be replaced at least every week. The CFDM was installed in-line in this sampling pipe. Its discharge (ca. 5 l/minute) was released to the tailwater circuit.

In the Handeck 2 HPP, the water was collected from the tailwater, following the same procedure as in Kaunertal HPP.

The turbidimeters were installed in the tailwater about 70 m downstream of the turbines at Kaunertal HPP and in the inlet of the cooling water system at Handeck 2 HPP.

2.2 Turbine inspections and geometrical measurements

At Kaunertal HPP, the machine group 5 (part-turbine 5A) was chosen to convey the remaining water in the final phase (from 1693 m a.s.l. to 1665 m a.s.l.) of the drawdown when the sediment concentration reached the maximum.

To check possible differences in turbine runner geometry during the monitoring period namely due to the passage of the sediment-laden water, 2 laser scans were conducted on 2/12/2015 and 15/5/2016 (showing the conditions from 14/1/2016), respectively. Within this period (during the drawdown), 5 more manual turbine inspections were made, consisting of specific points in the buckets and the width of the main splitter.

The laser inspections were performed by the company WESTCAM and included 3d scans of buckets 1, 2 and 3 of turbine 5. These scans covered whole buckets and main splitter. During the lowering of the reservoir level, it was not possible to measure the efficiency of the turbine due to ecological restrictions, namely the permissible SSC limit in the tailwater and in the InnRiver.

At Handeck HPP, two 3d scans of buckets 14 and 15 were made before and after the monitoring period.

3 Results

3.1 Discharge, volume, power output and reservoir level

The reservoir level and the discharge in the penstock were continuously monitored at both study sites. The results are presented in Figure 2. The full supply levels of the Gepatsch and the Räterichsboden reservoirs are 1’774 m a.s.l. and 1’767 m a.s.l., respectively.
The procedures followed by the operators to drawdown the reservoirs differed. In the case of Handeck 2 HPP the level reduction was more gradual than in Kaunertal HPP, where the drawdown was concentrated during one week in the beginning of December.

The total capacity of the Gepatsch reservoir is $138 \times 10^6$ m$^3$. During the monitoring period, the cumulated volume that was conveyed through the penstock was almost 10 % of the total reservoir volume ($12.1 \times 10^6$ m$^3$). The drawdown started at 1695 m.a.s.l, which is the minimum operating level of the reservoir.

Regarding the Handeck 2 HPP, the total volume of the Räterichsboden reservoir is $25 \times 10^6$ m$^3$ and the cumulated volume during the monitoring period was $10.7 \times 10^6$ m$^3$, corresponding to approximately 43 % of the total volume.

### 3.2 Suspended sediments

#### 3.2.1 Characteristics of the water samples

Two different approaches were followed to obtain water samples. In the case of Kaunertal HPP, a constant interval of one day was considered whereas in the case of Handeck 2 HPP the samples were obtained in irregular periods. They were more frequent during high gradients of the sediment-laden water density (measured by CFDM).

The SSCs of the water samples were evaluated by the gravimetric method ($SSC_G$), according to the following equation:

$$ SSC_G = \frac{W_{sed}}{V_{mix}} \text{ [g/l]} $$ (1)
where $W_{sed}$ stands for the weight of the dried sediments and $V_{misc}$ is the volume of the sediment and water mixture.

Figure 3(a) and (b) present the SSC$_G$ of the water samples and the water levels within the reservoir, for the Kaunertal and Handeck 2 HPPs, respectively. In the upper part of the figure, the bottles of the water samples are shown.

![Figure 3](image)

Figure 3 – Gravimetric SSC$_G$ of the sediment-laden water samples in (a) Kaunertal HPP and (b) Handeck 2 HPP.

While the SSC values were below 0.8 g/l at Handeck 2 HPP, two samples exceeded 10 g/l at Kaunertal HPP, with a maximum of almost 30 g/l. The SSCs sharply increased once a reservoir level of about 1710 m asl was reached for Handeck 2. For the Kaunertal HPP, a clear relationship between reservoir level and SSC is missing. The few SSC peaks rather seem to be due to stochastic processes of sediment deposit collapse in the Gepatsch reservoir. For each HPP, one sample was analysed in terms of density and mineralogical composition. Using the pycnometer, the density was evaluated as 2.763 g/cm$^3$ for Kaunertal HPP and 2.710 g/cm$^3$ for Handeck 2 HPP.

The mineralogical composition was evaluated by the Rietveld analysis. For Kaunertal HPP, the suspended sediments are mainly composed of quartz, Na-plagioklas, feldspar, mica and chlorite and the average particle hardness is 4.3 on the Mohs scale. The suspended sediments in Handeck 2 have a similar composition and an average particle hardness of 4.1 on the Mohs scale.

3.2.2 Suspended sediment concentration

As referred above, CFDM technique was used to determine the SSC of sediment-laden water (SSC$_C$). It was evaluated by water, particle and sediment-laden water densities, respectively, i.e. $\rho_w$, $\rho_p$ and $\rho_{mix}$ according to:

$$SSC_C = \left(\frac{\rho_{mix} - \rho_w}{1 - \rho_w/\rho_p}\right) + K \quad [g/l]$$

(2)

where $K$ is a constant obtained by calibration with the gravimetric SSC determination of the water samples. The water density, $\rho_w$, is a function of its temperature, $T$ (in °C):

$$\rho_w = 999.972 - 0.007(T - 4)$$

(3)

Before evaluating the CFDM data, the density of the sediment-laden water was compared to the gravimetric SSC from the water samples at corresponding times in order to evaluate the constant $K$ in the equation 2.

Figure 4(a) and (b) present the correlation between $SSC_C$ and $SSC_G$ after the evaluation of constant $K$, for the Kaunertal HPP and Handeck 2 HPP, respectively. Dashed lines represent the manufacturer’s specification, i.e. ±0.8 g/l of accuracy with respect to $SSC_C$. Most $SSC_C$ data fall within the manufacturer’s specification for the Kaunertal data, while the agreement with $SSC_G$ data is even better at Handeck 2 HPP. Note, however, that for $SSC_C < 4$ g/l, the manufacturer’s specification amounts to a relative measuring uncertainty of > 20 %, while it is < 10 % for rather large values of $SSC_C > 8$ g/l only.
Besides CFDM, the suspended sediment concentrations were indirectly evaluated by turbidimeters. In these cases the equipment was operated by the HPPs owners and the calibration relationships were obtained before the present monitoring periods with gravimetric SSC evaluated from water samples. The SSCs from CFDM and gravimetry were well correlated. The standard deviation of the differences between the SSCs from both techniques was $\sigma = 0.35$ g/l and 0.15 g/l for Kaunertal and Handeck 2 HPPs, respectively. The expanded SSC measuring uncertainty of the CFDM (at 95% confidence level) was estimated to be $2\sigma$ based on the data set. The time series of SSC obtained with the CFDM data according to equation 2 ($SSC_C$) and obtained with the turbidimeter according to calibration relationships ($SSC_T$) are presented in Figure 5. The SSC of the water samples obtained by the gravimetric method ($SSC_G$) and the level of the reservoirs are also plotted. Figure 5(a) and (b) show the results for Kaunertal and Handeck 2 HPPs, respectively.
Despite the limitations of the CFDM in the evaluation of low SSCs, the results show a good agreement between the $SSC_C$ and $SSC_G$ at the times when water samples were obtained.

The time series for Kaunertal and Handeck 2 HPPs show a very different pattern. In the first case, the SSC in the turbine water is characterized by very high concentrations from time to time followed by periods of very low concentrations. For Handeck 2 HPP, the concentrations are generally quite low and start only in the last part of the monitoring period to increase gradually.

Moreover, in case of Handeck 2 HPP, the turbidimeter result in higher SSC than the measured ones by the CFDM and by the gravimetric method for the water samples. As the turbidimeter was installed in the cooling water pump with the same water as the water analysed by the CFDM, one may attribute this error to a wrong calibration relationship of the turbidimeter as the SSC revealed an offset to the values obtained by the CFDM.

For Kaunertal HPP, there are significant differences between the SSC measured by the CFDM and by the turbidimeter. This is likely an effect of the location of each device. As referred to above, the CFDM was installed in the penstock right upstream of the turbine, while the turbidimeter was installed in the tailwater, approximately 70 m downstream of the turbines. Therefore, the time series is mainly characterized by very high gradients of SSC in the turbine water, while the pattern is rather damped for the tailwater data where a dilution of the sediments occur.

3.3 Turbine wear

As mentioned above, some buckets of the turbines were inspected by means of a 3d scan. The differences between the 3d scans before and after the monitoring period are presented in Figure 6.

![Figure 6](image)

The results revealed only small differences between the three buckets that were scanned for Kaunertal HPP. The abrasion is approximately between 1 and 3.5 mm with an average of about 2.5 mm. The abrasion takes place in the
whole bucket but is more pronounced in the lower part close to the bucket root. At the Kaunertal HPP the analysed runner was exposed to a suspended sediment load of almost 15,000 tons. In the case of Handeck 2 HPP, the wear was almost imperceptible for the inspected buckets due to the low sediment load.

4 Conclusions and recommendations

The sluicing of sediment-laden water through the power waterways is one option to cope with reservoir sedimentation provided that the effects of the suspended sediments on the turbine geometry are known.

In this paper the suspended sediment concentrations and the turbine geometry changes were analysed during the drawdown of two Alpine reservoirs. In both cases the drawdown was performed by conveying the water through the turbines.

Suspended sediment concentrations were monitored by means of CFDM and turbidimeters. As to turbine geometry, 3d scans of at least two buckets were conducted before and after the monitoring period.

The drawdown of the reservoir of Kaunertal HPP was mainly concentrated to one week in the beginning of December 2015 and the suspended sediment concentrations were characterized by rather high peaks and high gradients. In Handeck 2 HPP (drawdown in January and February 2016), the suspended sediment concentrations were quite low and reached about 1 mg/l only in the final phase.

The effects of the suspended sediments on the turbine wear reflect the different suspended sediment concentrations measured at each HPP. For Handeck 2 HPP, the 3d scans before and after the monitoring period reveal only slight changes, whereas for Kaunertal HPP the maximum differences amounted to approximately 3.5 mm.

References

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**Dr. João Nuno Fernandes** completed his studies in Civil Engineering at IST from the Lisbon University in 2003 and he obtained his PhD at the same university in the topic of flow characterization in compound channels in 2013. He worked in a consultancy firm and in the Hydraulics and Environmental Department of the National Laboratory for Civil Engineering in Lisbon from 2003 to 2014. He conducted consultancy and research projects dealing with flood management, hydraulic structures, water quality and sediment transport. From 2012 to 2014, he was Assistant Professor in the Civil Department of the New University of Lisbon and in January 2015 he joined ETH Zurich as a Postdoctoral Researcher.

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