Turbine abrasion: When is a Shut-Down Profitable

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Introduction

Turbine abrasion is a nuisance for power plants operating with sediment-rich water. High suspended sediment concentrations are typical for run-of-river schemes where sediment concentrations depend on the weather, the seasons and events such as landslides, and where sediment is only partially removed in settling facilities. These are usually designed to exclude sediment particles larger than 300 or 500 μm, and may be overloaded during extreme events or in case of insufficient flushing.

Needless to say, the damage to larger turbines can readily run into millions of dollars within a short time. The damage can occur fast enough that the value of power generated during the period is not enough to offset the cost due to sediments. The need for reliable real-time monitoring of sediments is obvious, as are criteria that recommend when it makes economic sense to close the intakes and shut down power production.

There are two components to this problem. First, a reliable measure of the damaging sediments. And second, clear guidelines for shutdown. The first part is now in adequate state of development – laser diffraction on-line instruments report sediment concentrations in size classes. The second part is far from settled. In this paper, we develop further some ideas that were first presented by the author at IAHR 2016 in Grenoble (Agrawal et al. 2016) and are similar to those by Felix et al. (2016). I propose that the knowledge of abrasion rate at a critical location, which we call hot-spots in the turbine, as function of sediment and flow parameters, can be a rational basis for recommending shutdown.

1. Background

It is accepted that sediment concentration, grain size, and hardness combine with flow velocity and material parameters to determine the instantaneous abrasion rate. It is important to have concentration and if possible particle size data in real time because these parameters may vary quickly. With instruments developed at Sequoia Scientific Inc., data on grain size distribution and concentration are now available in real time and such installations have proved themselves at installations in Asia and Latin America. For completeness, we summarily describe relevant technologies first, before discussing the main topic of setting shut-down thresholds.

1.1 Sensor Technologies

From the standpoint of turbine abrasion protection, sensors must measure the total concentration in near real-time, but also be able to partition the total suspended load into a less hazardous fine size class and a hazardous grain size range. Not trivial is the requirement of ability to measure high suspended loads that may reach 25g/l or higher. Here we only briefly mention competing technologies, with emphasis placed only on those that suit the application.

1.1.1 *Turbidity*: Optical turbidity is a well-established technique with dozens of manufacturers throughout the world. Light scattering from particles is sensed at some angle(s), and the scattering is calibrated in FNU or NTU's against Formazine standards. It is widely known that such light scattering signal, i.e. Volts/[g/*l*] strongly depends on grain diameter *d*, specifically, as 1/*d* when particle diameter >1μm. In other words, the conversion from NTU to sediment concentration depends on grain size. In a changing grain-size environment, the conversion function, also called calibration in the wider sense of the word, would need to be adapted frequently. A more serious difficulty with turbidity is that due to the 1/*d* dependence on sensitivity, *turbidity mostly misses the larger grains* which have higher erosion potential. Even worse, a high turbidity can be mistakenly interpreted as high concentration of hazardous grains, leading to a false shut down. I show this shortcoming of turbidity measurements in Fig.1 below.

1.1.2 *High Frequency Acoustic Backscatter* – the LISST-ABS instrument: Acoustic backscatter, similar to radar backscatter, fires a pulse of sound into water and listens for echoes. The strength of echoes is a measure of sediment concentration. The strength of backscatter depends on the acoustic frequency and grain size. The LISST-ABS operates at 8 MHz acoustic frequency. At this high frequency, the characteristic dependence of sensitivity (Volts/[g/*l*]) on grain size is very convenient for the present application. Whereas the sensitivity is low for smaller grains, it becomes nearly constant for grains of diameters between ~30 to ~500 µm. This means that LISST-ABS *ignores* the relatively harmless fine grains, and has nearly uniform sensitivity for the hazardous large grains. In other words, where turbidity fails, LISST-ABS excels. No false alarm will be raised by the LISST-ABS, unlike turbidity.

Because the LISST-ABS instrument is relatively new, there are no data from hydro installations reported yet. However, field tests were just recently conducted by the US government's Federal Interagency Sedimentation Committee, FISP (lead agency is USGS). Using a package of instruments including turbidity sensor and LISST-ABS they obtained vertical profiles of sediment measurement. The results, Fig. 1 confirm the distinction between the two sensors noted in the last paragraph. As shown, of the 3 profile sections shown in the inset, the middle sections

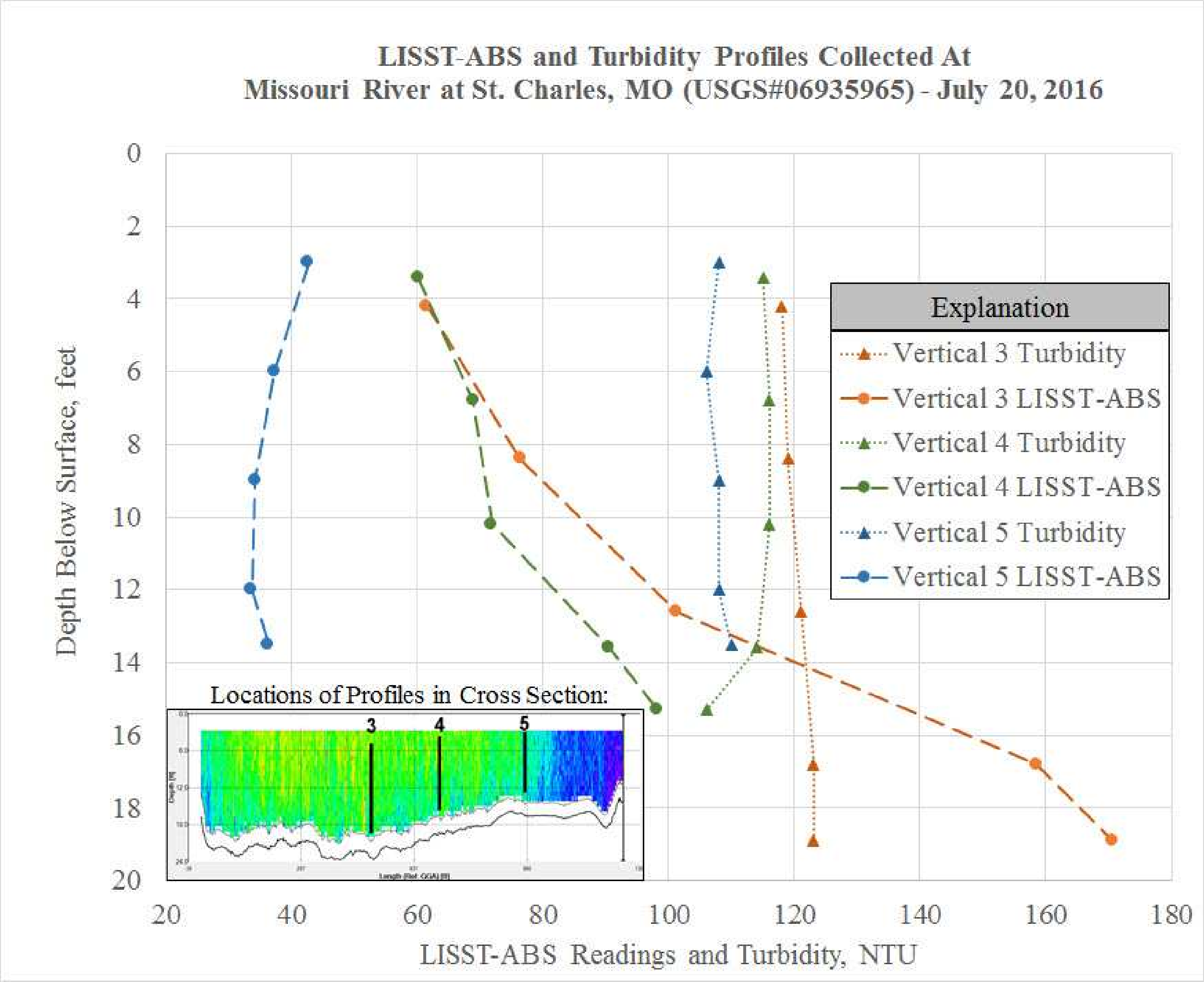

Fig. 1: Vertical profiles of sediment as seen by turbidity sensor, and contrasted with LISST-ABS. Mid-river data match well. The bank profile is explained by fine particles, determined by particle size analysis. [Data courtesy of and reproduced with permission of Dr. Mark Landers and Molly Wood, USGS.]

3 and 4 exhibited a strong increase in sediment concentration as seen by LISST-ABS, but missed by turbidity sensors. Such vertical structure is expected from classical mechanics, generally known as a Rouse profile. The acoustic profile at section 5 is proportionally weaker than turbidity data. This was reported by the scientists to be due to finer sediment near the bank, profile 5.

The USGS scientists also obtained physical samples of river water at varying depths to compare LISST-ABS signals. The match was reported to be remarkably consistent, as shown in Fig. 2.

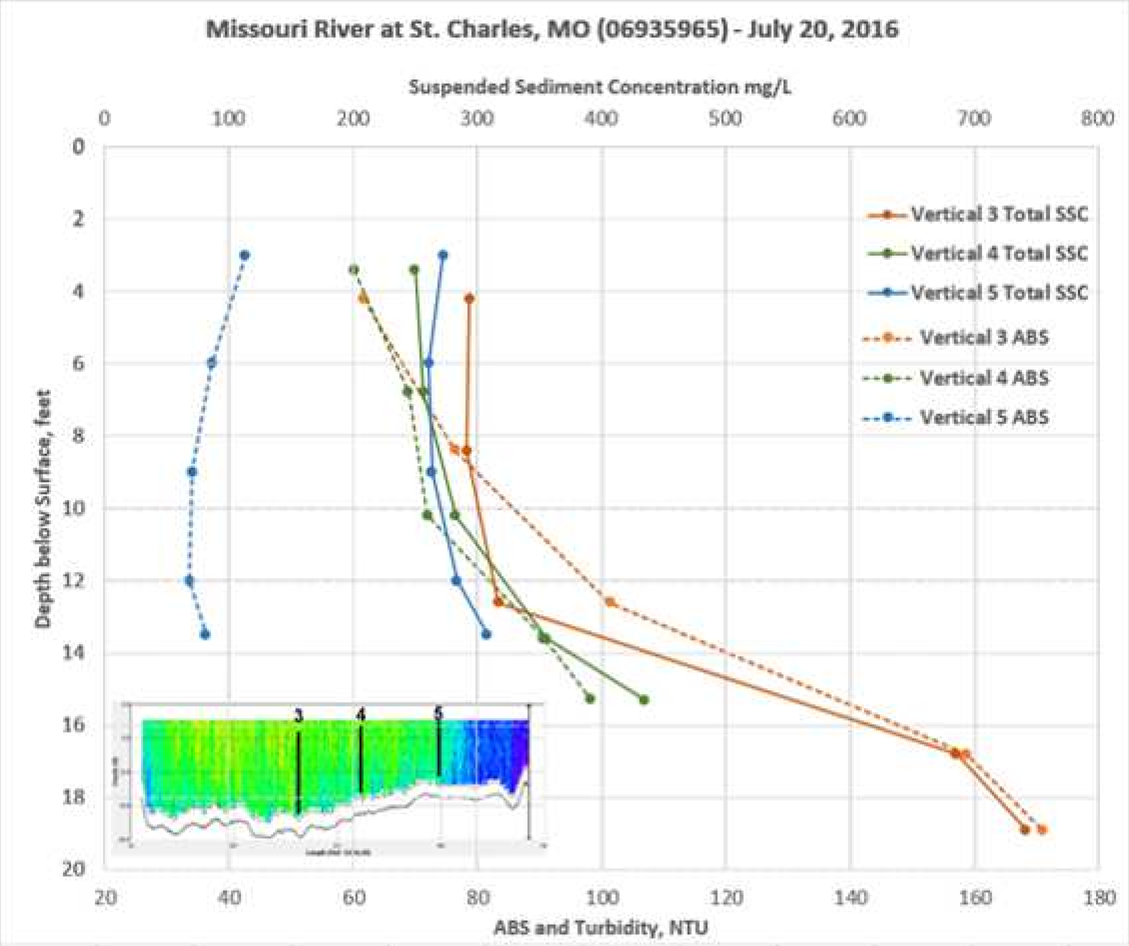

Fig. 2: Same as Fig. 1, but showing concentrations instead of turbidity. [Data courtesy of and reproduced with permission of Dr. Mark Landers and Molly Wood, USGS.]

1.1.3 ***Laser Diffraction:*** This technique (LD) has been around for over three decades, and laboratory instruments based on LD are offered by many companies. For use in hydropower, the instruments needed to be on-line, in routine industrial use, and reliable. This criterion was met by Sequoia Scientific, working with hydro companies in highly abrasive environments. Only LD has the capability to separate the total particle concentration into narrow size classes. The **LISST-Infinite** instrument made by Sequoia measures the volume concentrations of particles in 32 log-spaced size classes between 2 and 380 μm [recently expanded to 1-500 μm]. The measurement yields the best accuracy for total sediment concentration in environments with variable particle sizes. One can now separate the total concentration into, say, fine, medium, coarse size classes. The boundaries can be chosen by a user. Each size class can then have its own threshold for setting off alarms [Agrawal et al., 2011].

LD involves the measurement of laser light scattering at multiple angles, from a flowing sample. It is a delicate echnique requiring highly sensitive laser optics alignment and stability of the test cell. The additional difficulty of very high concentrations required use of short optical paths, and for extremely high concentration (approx.. >2000 ppm by mass for silt particles, depending on their sizes), the capability to carry out a dilution step. The currently installed systems have been in service up to 5 years, with only routine maintenance. The data can be viewed on multiple work stations if written on an accessible server (e.g. Dropbox).

LISST-Viewer Instrument Monitor Mode - Sequoia Scientific, Inc. - Tala - Bhutan

Last PPM Value 203

Last PPM Value 196

Last PPM Value 295

Last PPM Value 695

No warnings or errors

X-Axis Time Period Scaling: 1 week

Tank Level 100 %

*Fig.3: Typical **LISST-Infinite** strip-chart display of total sediment concentration (bottom), concentration of fines (second from bottom), medium (third), and coarse grains (top). Red lines show alarm thresholds set by user. [From Agrawal et al., 2016]*

2. Shut-Down Criteria

Even after measurement technologies became available, the question remained: When should we shut-down a hydropower-plant *to save money from damags?*. In one case, the need for power was so great that despite LISST-Infinite reports of very high concentrations, the political directive was to keep producing power. In other cases, lacking clear guidelines, it is typical for power plants to keep operating. The need for objective guidelines is clear. Below, we present two ideas.

The first we proposed at IAHR 2016 in Grenoble (Agrawal et al. 2016). This idea takes into account the instantaneous sediment flux (ISF). Similarly, in a later session in Grenoble on the same day, Prof. R. Boes from VAW of ETH Zürich proposed to consider the fine-sediment induced costs per kWh (Felix et al. 2016).

The second, newer idea in this paper proposes to consider the instantaneous abrasion rate (IAR) and its associated cost compared to the revenue from power sales per turbine.

2.1 The Instantaneous Sediment Flux Criterion (ISF): This is a simple idea based on the assumption that a certain amount of fine sediment will run through before refurbishment of the turbine components is required. Consequently, if SSL is the total suspended sediment load passing the turbine before refurbishment (tons), and the C is the cost of repair ($), then the specific cost of sediment passage is C/SSL. Let the hourly passage of sediment (sediment flux, in tons/hr) be called F. At a critical flux of F_{crit}, the cost of repair per hour of operation becomes C F_{crit}, / SSL. The critical flux then is defined as the flux at which the revenue generation R ($/hr) is smaller than the cost of operation, i.e. when

$$C * F_{crit}, / SSL < R \tag{1}$$

Here, the required inputs are the refurbishment cost of C, and the suspended sediment load SSL. The latter quantity is generally not known with sufficient accuracy. That is a weakness of the ISF approach.

From the discharge Q, and the sediment concentration reported by the LISST-Infinite, the sediment flux can be computed to determine the critical flux F_{crit}. A shortcoming of this approach is that the effect of potentially variable flow velocity on abrasion is not considered.

2.2 The Instantaneous Abrasion Rate Criterion (IAR): The key attraction of the abrasion rate formulation is the relatively more robust basis of the required abrasion rate parameter. The sediment load that is allowed to pass through a turbine before maintenance becomes necessary is not easy to quantify, since grain size and flow velocity play significant roles. Instead, the abrasion rate that we recommend using, is a localized number for a hot spot. It can be measured relatively easily. Formulations also already exist.

The IAR criterion first makes the reasonable assumption that it is not necessary to know the global erosion of machinery. It is sufficient to only know the abrasion rate of a local hot-spot. For example, such a hot spot would be on the splitters of a Pelton turbine runner. In this case two parameters are required: (i) the instantaneous abrasion rate as function of grain size, water velocity, grain hardness; and (ii) maximum tolerable abrasion before refurbishment becomes necessary. Of course, the refurbishment cost is needed, but this is probably the best constrained variable.

Felix (2017) cites the Sulzer Hydro formula (partly published in DWA 2006)to provide the instantaneous abrasion rate (in μm/hr) as:

$$\Delta d_e / \Delta t = \underline{\xi} [\ 1.6 * 10^{-10}\, w^{3.0}\, SSC\, q\, f\,(d_{50})\, z_0/z_2\ ] \qquad [\mu\text{m/hr}] \tag{2}$$

where w is the characteristic relative velocity (m/s), SSC is sediment concentration (g/L), q is mass fraction of quartz, $f(d_{50})$ is a size-dependent factor with value around $1.25.10^6$, and z_0 and z_2 are, respectively, the number of jets and number of buckets on a Pelton runner. We have introduced a correction factor ξ to absorb fixed factors specific to a particular turbine or hot-spot.

As an example, for a Pelton runner, two jets and 20 buckets, with w = 50 m/s, for coarse grains ($f \approx 1 * 10^6$), SSC of 20 g/L, and quartz fraction of 0.5, the abrasion rate would be:

$$\Delta d_e / \Delta t = 20\ \mu\text{m/hr}.$$

At this rate, a 50 hr-operation would lead to 1 mm of abrasion depth. If turbine repair is necessary at an abrasion depth of 5 mm, i.e. 250 hours under this high sediment concentration, then the repair cost can be spread over 250 hours. Assuming a $1M total repair cost, the cost per hour of operation is $4000. At an electricity rate of $0.05/kWh, this implies that if power production is less than 80 MW, shut down is profitable at SSC of 20 g/L.

In this example, we have used a hypothetical number for the refurbishment cost. These costs must include all components such as loss of revenue generation, depreciation, capital costs, etc. Since not all particles have the same size, it is proposed to calculate the erosion rate in Eq. (2) as an integral of the SSC_i in some size classes multiplied by the corresponding relative erosion potentials $f(d_i)$. This fraction-wise calculation of the erosion rate reduces the uncertainty in case of significant spreading of the PSD

3. Discussion

The points of this paper are:

1. Optical turbidity sensors are unsuitable for turbine abrasion protection;
2. Acoustic or laser techniques presented here are suited to generate data on large grains, which are ignored by turbidity;
3. We have examined two approaches to shutdown criteria: the instantaneous sediment flux method ISF, and the instantaneous abrasion rate method IAR.
4. The IAR method provides a more rational estimate of instantaneous cost due to abrasion, and therefore a running parameter that is *directly related to abrasion rate.*

Finally, we note that this method does not require global average abrasion over a bucket or blade. The location within the turbine which is most critical with respect to abrasion, on the most critical component only is involved. That limits the necessary further research on calibration parameters and the effect of particle size $f(d)$.

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The Author

Yogesh (Yogi) Agrawal: Dr. Agrawal did his undergraduate studies in India and received his doctorate in Fluid Mechanics from Univ. of California, Berkeley (1975). His research career spans fluid mechanics of combustion, mechanics of sediment transport in oceans and freshwater, and in development of instruments to advance measurement technologies. He is the inventor of the LISST series particle sensors manufactured by his company, Sequoia Scientific, Inc. (www.SequoiaSci.com)