Field application of a multi-frequency acoustic instrument to monitor sediment for silt erosion study in Pelton turbine in Himalayan region, India

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Abstract. High sediment load passing through hydropower components erodes the hydraulic components resulting in loss of efficiency, interruptions in power production and downtime for repair/maintenance, especially in Himalayan regions. The size and concentration of sediment play a major role in silt erosion. The traditional process of collecting samples manually to analyse in laboratory cannot suffice the need of monitoring temporal variation in sediment properties. In this study, a multi-frequency acoustic instrument was applied at desilting chamber to monitor sediment size and concentration entering the turbine. The sediment size and concentration entering the turbine were also measured with manual samples collected twice daily. The samples collected manually were analysed in laboratory with a laser diffraction instrument for size and concentration apart from analysis by drying and filtering methods for concentration. A conductivity probe was used to calculate total dissolved solids, which was further used in results from drying method to calculate suspended solid content of the samples. The acoustic instrument was found to provide sediment concentration values similar to drying and filtering methods. However, no good match was found between mean grain size from the acoustic method with the current status of development and laser diffraction method in the first field application presented here. The future versions of the software and significant sensitivity improvements of the ultrasonic transducers are expected to increase the accuracy in the obtained results. As the instrument is able to capture the concentration and in the future most likely more accurate mean grain size of the suspended sediments, its application for monitoring silt erosion in hydropower plant shall be highly useful.

1. Introduction

For the management of rivers, dams, reservoirs, and hydropower plants, the measurement of suspended sediment concentrations are important particularly due to increasing erosions resulting from climate changes [1,2]. Reliable measurements of the Total Suspended Sediment Concentration (TSS) are mostly achieved by taking water samples manually and gravimetric analysis in the laboratory. But this procedure does not provide high spatial and/or temporal resolution of TSS in a river or reservoir system. Existing sediment concentration instruments like optical turbidity probes and acoustic backscattering require regular calibration by taking water samples since the particle size distribution might change. This procedure limits the real-time capability as that the amount of total suspended solid/sediments can be under or over estimated. The acoustic measurement principles provide spatial information, which can be used for data analysis and sediment transport information as well [3].

High sediment transport rate into hydropower plant system causes hydro abrasive erosion to hydro-turbine parts, hydraulic structures and sediment removal system [4]. The erosion of turbine parts leads
to abetting of cavitation, pressure pulsations, vibrations, mechanical failures and frequent shut downs [5]. These problems have large effect on run-of-river schemes which have no storage capacity for settlement of sediment. Realizing the problem in Himalayan Rivers, Mann [6] classified the Indian power plants in three categories: Category A (repair after each 2 monsoons) to Category C (repair after 7 monsoons) based on their vulnerability to silt erosion. Continuous TSS measurements are also useful for other applications like sediment transport monitoring in rivers [1,7]. The sediment mass flow (TSS data in combination with flow metering data) can be estimated continuously in real-time.

The need of measuring TSS and particle size distribution (PSD) variations in hydropower plant is emphasized by different researchers [7,8,9]. Rai and Kumar [10] discussed different systems available for continuous suspended sediment monitoring with respective advantages and disadvantages. Acoustic and laser diffraction technology have ability to provide both suspended sediment concentration and size. However, the laser diffraction technology is limited by sediment concentration range; the limiting range is typically 2 g/l for silt particles. This limiting range of concentration is dependent on PSD, path length of measurement in instrument and particle shapes. The acoustic technology is well suited for higher concentrations with main drawback of complexity in analysing the backscattered signal. A single frequency acoustic device is capable to provide only sediment concentration whereas the use of multi-frequency acoustic systems is not reported widely [10].

This research article presents the first field application of a multi-frequency acoustic instrument, SediScat [11-13], tested successfully in the laboratory, to measure sediment concentration and the mean grain size ($D_{50}$) continuously at a hydropower plant in Himalayan region having severe silt erosion issues. The site conditions and mounting of the multi-frequency acoustic instrument SediScat has been explained subsequently. The methodology adopted and the outcomes from this study along with the uncertainty involved have been presented. Apart from hydropower managers, this study can be useful for environmentalists, hydrologists and sediment experts interested in measuring sediment parameters continuously.

2. Case study site
The study site Toss hydropower plant with 10 MW capacity is a located in Kullu district of Himachal Pradesh, India at the river Tosh, a tributary to Parbati River. There are two Pelton turbine units with a designed head of 174 m and total discharge of 7 cumecs. The desilting tank with forebay of the plant is designed to remove sediment particles with a diameter larger than 200 micron. The measurement location of sediment was selected near the penstock intake in desilting tank (see Fig. 1) to ensure that the measurement of sediment concentration and grain size was representative for the hydro-abrasive erosion study. This location facilitated in easier installation and maintenance of the SediScat.
Figure 1. SediScat installation location in desilting with forebay tank of Toss hydropower plant

Fig. 2 shows the schematic of the measurement location of SediScat sensor and manual sampler. The depth of measurement for both measurement techniques was same as seen in Fig. 2. However, the spacial location of SediScat sensor and manual sampling point varied within 1 meter of horizontal distance to ensure no damage could occur to submerged SediScat sensor at the time of manual sampling. Here, it was assumed that the suspended sediment particle will have similar properties at same depth.

Figure 2. Schematic of sampling cross section at desilting tank

Manual samples were collected twice daily at 8 am and 4 pm from 28 May 2015 to 6 August 2015 in 500 ml plastic containers. Initially a manual sampler was used for sample collection which was later replaced with a pump sampler. The samples were carefully collected as per IS 4890 [14] at the same water depth of SediScat to capture true representative of sediment concentration and size.
3. Methodology

3.1 Measurements using SediScat

The method used in SediScat is based on the theory of sound propagation and the SONAR equation (eq.1) for estimating the suspended sediment concentration [15].

\[
EL = SL + C - 20 \log(\eta R) - 2\alpha R + 10 \log \left(\psi \frac{c \tau}{2}\right) + BS_v
\]  

(1)

where \( EL \) is the echo level in Decibel (dB), \( SL \) is the source level (dB), \( C \) is a coefficient related to the transducer (dB), \( R \) is the range from the source to the targets area, \( \eta \) is the near-field correction, \( \alpha = (\alpha_w + \alpha_s) \) is the attenuation coefficient (dB/m) due to water and sediments, \( \psi \) is the equivalent aperture (solid angle, in steradians) of the transducer(s), \( c \) is the velocity of the acoustic wave (m/s), \( \tau \) is duration of the transmitted signal (s), \( BS_v \) is volume backscattering strength (dB). Details of the model implemented in the SediScat prototype have been described in [11,12].

The calibration free approach could be realized by narrowing the number of un-known parameters of the algorithm down to three:

- Mean of the particle size distribution
- Slope of the cumulative particle size distribution
- Total suspended sediment concentration (TSS)

By using minimum 3 distinct measurement frequencies each collecting different backscatter information from the suspended sediments depending on their concentration and grain size, the algorithm can run iteratively as shown in Fig. 3 and solve the inversion equation [13]. A fourth measurement frequency has been added to ensure that sufficient information is captured in the case one frequency would not record adequate strong backscatter intensity. The used prototype is currently operating at 0.5, 1.0, 2.0 and 4 MHz and the algorithm is using the measured echo levels (EL) in an iterative approach (see also Fig.3).

Required input parameters are salinity (S), temperature (T) and pH in the measured water column and the installation depth (Z) of the transducers. Salinity, temperature, pH and depth are currently provided by the user and keyed in manually. In a later version, these parameters will be measured in real-time and used automatically by the algorithm.

![Figure 3. Simplified flow chart for estimation of suspended sediment concentration (TSS) using multi-frequencies [13]](image)
The measurement principle has been tested under laboratory conditions with various sediment size classes [11,12]. An example is shown in Fig. 4.

Figure 4. Test results of the SediScat Prototype for 2 different particle size distributions (Experiment A and B) and sediment concentrations [11]

The SediScat instrument measures the received backscatter signals as voltage signals. The instrument stored 200 raw data before averaging in order to reduce the noise floor of the measurement signals. These data were converted to Decibel (dB). This measurement process lasted approximately 1.5 minutes whereas the algorithm calculating the total suspended sediment concentration required up to 3 minutes computational time. Therefore, the minimum measurement frequency of the prototype instrument was 5 minutes.

The prototype instrument failed to record backscatter data correctly from August 7th 2015 onwards.

3.2 Analysis of the collected samples in laboratory

The collected samples were brought to laboratory for analysis and analysed using IS 6339 [16]. Further, other methods like laser diffraction and conductivity probe were used. The flow chart in Fig. 5 shows the process of analysing manual samples. In drying method, total solid concentration (TS) in parts per million (ppm) by mass present in a sediment sample was calculated by drying a known weight of sample and using following equation (2).

\[ TS = \frac{W_{B+TS} - W_B}{W_{W+B+TS} - W_B} \times 10^6 \]  

where TS is total solid in ppm by mass, \(W_{B+TS}\) is weight of beaker and total solid after drying, \(W_B\) is initial weight of beaker and \(W_{W+B+TS}\) is weight of beaker and sediment sample from site. A high precision balance with least count 0.1 mg was used for weighing. The total suspended solid (TSS) was calculated using equation (3).

\[ TSS = TS - TDS \]  

where TDS is total dissolved solid in ppm by mass present in sample.

In filter method, 100 ml sample from site was filtered with a 0.45 µm filter and TSS was calculated using equation (3).

\[ TSS = \frac{W_{F+TSS} - W_F}{100} \times 10^6 \]  

where TSS is total suspended solid in mg/l (equivalent to ppm), \(W_{F+TSS}\) is weight of filter paper with TSS, and \(W_F\) is initial weight of filter paper.
The conductivity probe used for measuring TDS was made by Hach (Model: HQ 40d). The laser diffraction instrument used for measuring every sample in laboratory was made by Sequoia (Model: LISST-Portable). Few samples for sediment size verification were measured with instruments made by Malvern (Model: MS 3000), Retsch (Model: Camsizer XT) and Horiba (Model: LA 950).

Twice daily samples collected at desilting tank

Manual samples brought to laboratory for analysis

Laser diffraction instrument used for finding the sediment size distribution and volumetric concentration for each sample

Drying method used to find Total Sediment (TS) concentration of each sample

Few samples are analyzed with different instruments for cross checking of size distribution

A conductivity probe used to find Total Dissolved solid (TDS) for each sample

Total Suspended Solid (TSS) is obtained using equation:
TSS = TS - TDS

Few samples are analyzed with Filter Method (Filter size 0.45 µm) for cross checking of TSS

4. Results and discussions
The result of measurement of sediment median grain size ($D_{50}$) and sediment concentration are provided in following sections.

4.1 Measurement of median grain size ($D_{50}$)
The median grain size ($D_{50}$) as a result of the SediScat recordings and data of the LISST-Portable analysis from the water samples are provided in Fig. 6. The measuring range of SediScat was starting from 38µm only, whereas the desilting tank was containing most of the particles in the $D_{50}$ range of 20-40µm. Hence, a large deviation of particle size distribution is expected as the lower two ultrasonic frequencies (0.5 MHz and 1.0 MHz) will not always receive sufficiently strong signals for such small grain sizes. Higher frequencies like 2 MHz and 4 MHz are more sensitive to smaller sizes. In the case that less than 3 sensors provide a significant measurement value (see section 3.1), all equations cannot be solved as required by the algorithm. Therefore, the current software was tuned to prioritize more on accuracy of the concentration results than on the median grain size. In future versions of the SediScat instrument, more sensitive transducers will be used in particular for the lower frequencies. In addition, the user can select the expected grain size of the suspended sediments, if such site specific information is available. This selection will be possible even if expected range is not within the measurement range of the instruments (here 38µm - 500 µm). Both parameters; particle size and concentration, will have the same priority and weighting factors, when the expected size is within the range. If the size is below the specified limit (here 38 µm), the instrument will focus on the accuracy of the sediment concentration only. Otherwise the estimated sediment concentration will be calculated significantly too low.

4.2 Measurement of suspended sediment concentration (TSS)

Fig. 7a and Fig 7b show all SediScat recorded data TSS and the gravimetric laboratory TSS results.

![Figure 7a. Comparison of SediScat and manual sample TSS concurrently available data from 27th May – 24th June 2015](image)

![Figure 7b. Comparison of SediScat and manual sample TSS concurrently available data from 25th June – 6th August 2015](image)

Fig. 7a and 7b shows the concurrently available suspended sediment concentration (TSS) data from SediScat and manual sampling. From beginning to 24th June 2015, there is a close similarity of the instrument readings compared to the manual samples with very few outliers. Sediscat was unable to detect decreasing TSS from 24th June to 3rd July 2015 whereas larger number of outliers existed after 7th July 2015. This behaviour of the instrument can be attributed to the fact that there might be...
problems in signal receiving due to long term deployment or some permanent debris attached on the ultrasonic sensor head (as there was no wiper or any other cleaning procedure administered to the local technicians). It was required to turn on the instrument every time after power cuts, which could also have affected the measurements and was the major cause of the time mismatches between instrument readings and manual water sample collection.

The SediScat prototype was the first version used for long-term deployment in the field. The main limitation of this prototype is the minimum grain size detection limit of 38μm. This forces the algorithm to find a stable solution with the priority on TSS (and not on the grain size). Therefore, the TSS deviation from the sampled data is much smaller than the grain size deviation. In addition, the timing between the physical water sampling and the SediScat prototype was not always synchronized resulting in time differences of some minutes up to an hour. The SediScat prototype did not allow to log the water temperature also, which has an impact on the underwater acoustics and accuracy of the SediScat algorithm results. A constant water temperature of 12°C during the measurement campaign was assumed.

The location for taking physical water samples and the SediScat measurements (see Fig. 2) was not exactly the same. It is assumed that the variation was low for high discharge/flow conditions. But sediments plumes in the desilting tank could be visually observed for low flow conditions. These plumes might also have caused different measurement results between manual sampling and instrument recordings when both were not conducted at the identical location.

5. Uncertainty in measurement

5.1 Uncertainty in SediScat measurement

The main uncertainties in the SediScat have been found as follows:

1. Measurement of the 4 received echo levels (for the 4 sending frequencies 0.5, 1.0, 2.0 and 4.0 MHz). These echo levels are determined by averaging over at least 200 raw data. This process improves the signal-to-noise ratio. Further studies will determine if the number of raw data has to be increased or decreased. The 4 echo levels are the input parameters for the algorithm to estimate the sediment concentration and grain size.

2. Algorithm: The inversion equations of the underlying model (see eq. 1) cannot be solved analytically. The iterative solver in the algorithm has several discretization steps, e.g. mean grain size ±5%.

These two main factors lead to the current uncertainty of the algorithm of ±20% for the estimation of the sediment concentration and mean grain size and have been established in the laboratory [11, 12].

5.2 Uncertainty in laboratory analysis

The uncertainty in the study is computed with help of uncertainty analysis formulae given by Klein and Mcelintock [17], which estimates the uncertainty in a parameter as given below.

\[ \delta Y = \sqrt{\left( \frac{\partial Y}{\partial x_1} \times \delta x_1 \right)^2 + \left( \frac{\partial Y}{\partial x_2} \times \delta x_2 \right)^2 + \left( \frac{\partial Y}{\partial x_3} \times \delta x_3 \right)^2 + \cdots + \left( \frac{\partial Y}{\partial x_n} \times \delta x_n \right)^2} \]

\[ \text{% uncertainty in measurement of } Y = \frac{\delta Y}{Y} \times 100 \% \]

where \( \delta Y \) is absolute uncertainty in measurement of \( Y \), which is a function of independent variables \( x_1, x_2, x_3, \ldots, x_n \). The values \( \delta x_1, \delta x_2, \delta x_3, \ldots, \delta x_n \) are the uncertainties in measurement of basic independent variables \( x_1, x_2, x_3, \ldots, x_n \). The calculated uncertainty in total suspended solids measurement (drying and filtering methods) was 1.77% due to use of high precision weighing balance of least count 0.1 mg. The uncertainties due to sub-sampling, error in sample collection and flow variation, sample handling and storage were neglected.

6. Conclusion

IEC 62364 [18] emphasises to have sediment parameters like sediment concentration, size, shape and mineral composition for erosion study. The advancement in technologies has allowed development of instruments to measure sediment concentration and size with high temporal frequency. Use of these devices in erosion study will increase the reliability/repeatability/reproducibility.
In the view of this first deployment of SediScat in field application, the sediment concentration data was found to have reasonable accuracy, in particular in view of the fact that the instrument was not field-calibrated and did not require any calibration. The sediment size information is expected to improve with development of software and measuring capability of the instrument in lower size range.

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