Hydro-abrasive erosion in Pelton buckets: Classification and field study

Anant Kr. Rai¹,², Arun Kumar, Thomas Staubli³

¹ Alternate Hydro Energy Centre, IIT Roorkee, Roorkee, India
² Lucerne School of Engineering and Architecture, Fluid Mechanics and Hydro Machines, Switzerland

ABSTRACT

In fragile mountainous regions, hydropower plant components face severe hydro-abrasive erosion, resulting in reduced efficiency, frequent interruptions in power generation and downtime during maintenance. In this study, the hydro-abrasive erosion is classified and measurement methodology is proposed for various erosion patterns in Pelton buckets. In Pelton buckets of a high head hydropower plant located in the Himalayas in India, the amount, pattern and depth of erosion were measured during the study period May-October 2015. The size, shape and concentration of the suspended sediment passing through the turbines were obtained from manual samples and with an online multi-frequency acoustic instrument.

In uncoated buckets, the average reduction of the splitter height and the abrasion in the cut-out portion were 3% and 5% of the bucket width respectively, whereas the maximum erosion depth of ripples in the curved zone was 1.5%. 73% of suspended sediment consisted of silt particles with median grain size (d50) between 20 and 40 µm. With coefficient of variation 75%, 32% and 1% for concentration, d50 and shape respectively, 12,540 t of suspended sediment passed through each turbine unit during 3180 h of operation. This study seeks to facilitate the measurement of hydro-abrasive erosion in Pelton turbines and suspended sediment parameters.

1. Introduction

In geologically young mountains like the Andes and the Himalayas, most of the streams contain high suspended sediment concentration (SSC) during the rainy/monsoon seasons. The suspended sediment causes hydro-abrasive erosion in hydraulic turbines and other project components coming in direct contact with moving sediment laden water. The hydro-abrasive erosion poses challenges for smooth and efficient operation of existing hydropower plants (HPP) as well as for the development of new HPPs. In the present day, hydro-abrasive erosion (henceforth referred to as “erosion” for simplicity) has gained much needed attention as it causes the loss of power generation as well as expensive maintenance [1]. The loss of generation is due to reduced efficiencies of generating units due to profile changes of the turbine blades/buckets caused by erosion [2]. Run-of-river (ROR) plants face high erosion as they do not have storage options for settling and removing the suspended sediment. For ROR schemes with high heads, even small sediment particles cause high erosion, especially in Pelton turbines due to the high velocity. Though several researchers have identified parameters involved in the erosion of Pelton turbines such as suspended sediment concentration, size, shape, mineral contents, material composition, erosion velocity and duration of operation [3–5], the quantitative information about influence of these parameters is not fully known. Though the International Electrotechnical Commission (IEC) [6] provides an empirical model for calculation of erosion in hydro-turbines, model coefficients related to Pelton turbines are not provided due to lack of field studies.

In the laboratory, the erosion is usually measured with weight loss [7,8], thickness loss and surface roughness change [3], due to the ease of measurement of small sized test specimens. Rajkarnikar et al. [9] used paint to visualise erosion on small Francis blades in the laboratory. However, the measurement of erosion in hydro-turbines of actual HPP is challenging because of irregular curved profiles of turbine components, varying erosion thickness with ripples, non-availability of reference surfaces due to change of original profiles, and the large size of turbine components [3]. In actual HPPs, thickness reduction provides the quantity of erosion, which can be measured using templates and thickness gauges [4,10]. Bajracharya et al. [11] studied erosion in the 2-jet Pelton turbine of Chilime HPP (2 × 11 MW) in Nepal and related the erosion to the efficiency reduction of the turbine. The erosion of needles and nozzle rings was measured with a stylus probe apart from measuring suspended sediment with sieves and mineral analysis of manual samples in the laboratory. They found an erosion depth of 3.4 mm/year for needle and bucket, resulting in loss of 1.21% efficiency of turbine, caused by 80% hard mineral quartz. Boes [12] studied erosion in the 4-jet Pelton turbine of Dorferbach HPP (1 × 10 MW) in...
Austria from May to October 2008 by (a) measuring the increase in splitter width (17 times for 3 Pelton runners) using templates and (b) measuring SSC and particle size distribution (PSD) continuously with an optical backscatter turbidimeter as well as a laser diffraction instrument along with manual pumped sampling. To forecast erosion and to assess the effect of counter measures, an erosion model was developed for the plant studied.

Recently, researchers applied imaging and video techniques to monitor erosion in turbine components to facilitate inspection without major dismantling, lesser inspection time and to provide offline image comparison [13,14]. Dahlhaug and Thapa [13] inspected Francis turbines in Jhimruk HPP (3×4 MW) in Nepal with a borescope to observe damages like holes and cut-offs. In some major erosion studies [4,11,14], researchers obtained and analysed the erosion from the difference of initial and final state of turbine components. Abgottspon et al. [14] measured erosion of coated Pelton buckets with an optical 3D-scanner from the year 2012–2014 in a 515 m high head Fieschertal HPP (2×32 MW) in Switzerland. The coating thickness distribution inside Pelton buckets was also measured using a thickness gauge based on magnetic induction. The SSC and PSD were measured continuously with turbidimeters, acoustic and laser diffraction instruments. During the whole study period, the splitter height reduced by 3–5 mm in 2012 only due to one major sediment event of 20 g/l SSC. The erosion in coated and uncoated buckets differs considerably and use of these modern techniques for uncoated Pelton buckets is rarely reported.

IEC [6] recommends the measurement of erosion thickness in uncoated Pelton buckets at minimum 5 points per half bucket and splitter width on top at 3 locations (front, middle and back) using templates. However, this methodology cannot quantify various erosion forms in Pelton buckets, especially in cut-out region. In this study, an attempt
has been made to a) identify and measure various erosion patterns, b) classify erosion in Pelton bucket and c) propose new erosion parameters based on the available literature as well as the observations from Toss HPP (2×5 MW), located in Himalayan region of India. To measure erosion and to obtain proposed erosion parameters in an uncoated Pelton turbine, two uncoated buckets of Toss HPP were 3D-scanned and the images so obtained were analysed. Further, erosion in coated buckets of the same plant for the same duration was also measured. In another attempt, the outside of all the buckets were painted and the paint removal patterns due to erosion were analysed. Suspended sediment shape was quantified with respect to sphericity and aspect (b/l) ratio, commonly used parameters for sediment shape, from manual samples using dynamic imaging technique.

2. Definitions and case study site description

Erosion is defined as the phenomenon which removes material from buckets due to collision or friction of solid particles entrapped in the flowing water on/along surfaces. The term ‘coated’ is used to specify a hard layer over the surface and ‘bucket’ refers to Pelton bucket without coating unless otherwise mentioned. To explain the erosion pattern in specific locations of the bucket, the bucket is divided lengthwise from the rotation centre outwards as well as breadthwise in three parts (Fig. 1). The terms such as cut-out, splitter, bucket tip, outer edge and bucket width are also indicated in Fig. 1.

The study site, Toss HPP (2×5 MW), is located in the Himalayan hills of Kullu district in Himachal Pradesh, India, at the river Tosh, a tributary of Parbati River. The plant has two vertical 4-jet Pelton turbine units installed with a design head of 174 m and a unit discharge of 3.5 m³/s. The Pelton turbine in Unit-1 had uncoated buckets whereas Unit-2 had coated buckets. The combined desilting tank and forebay of the plant are designed to remove sediments with particle size greater than 200 µm.

3. Classification of erosion patterns in a Pelton bucket

Though the amount of erosion in bucket depends on the suspended sediment and flow parameters, erosion patterns are similar for various regions of the bucket like splitter, cut-out and curved zone (Fig. 2). From photographs of eroded buckets reported in literature [1,10,15,16] and the present study site, distinct erosion patterns are found in splitter, cut-out and curved zone (Fig. 2).

Though the erosion in hydraulic turbines is broadly classified based on the appearance of eroded surfaces, no methodology for measurement was discussed [5,17]. To distinguish and quantify erosion in buckets, a classification with five categories, named as E1, E2, E3, E4 and E5, illustrated schematically in Fig. 3 is proposed here. The possible causes, parameters to quantify and methods of measurement for various erosion classes are presented in this section.

3.1. Wavy erosion of the splitter top (E1)

The initially thin and sharp splitter top of bucket, Zone 1, is changed to a flat surface with a wavy pattern in radially inward direction with respect to the Pelton runner axis (Fig. 3c). This wavy shape of eroded splitter is formed by the varying erosion conditions throughout the splitter length. The variation in quantity of jet inflow, impingement location and angle causes variation in erosion conditions (Fig. 4).

The high impingement angle causes impact erosion due to plastic deformation and indentation in the splitter region, Zone 1 [18]. The maximum and minimum erosion are found in the middle and rear parts of the splitter respectively. The erosion type E1 can be quantified with reduction in splitter height (Δh), increase in splitter width (Δb) and wavelength of erosion waves (Δl) (Fig. 3c). As these parameters vary along splitter length, average values in the front, middle (near the pitch circle diameter PCD) and rear parts need to be obtained with templates. Δb and Δl can also be measured with a simple ruler.

3.2. Ripple erosion in curved surfaces (E2)

The curved region of buckets, Zone 3, is deformed like ripples all over the surface along the direction of flow (Fig. 4b), as shown
schematically in Fig. 3a. These ripples are formed along the bucket surface due to sliding and scratching of sediment particles, separated from flow-streamlines caused by the low radius of curvature and the associated very high accelerations [19,20]. The low impingement angle causes cutting and abrasive erosion due to plastic deformation as well as ploughing in the curved region, Zone 3 [18]. The magnitude of ripple erosion varies in different parts with a maximum value in the middle part of the bucket. The erosion type E2 can be quantified with thickness loss and wavelength of ripples in radial (ΔBr) and in outlet directions (ΔBo) (Fig. 3a). For measurement of thickness loss, templates are required; however, a simple ruler can also provide the ripple details inside the bucket.

3.3. Bulging erosion lines between splitter and curved surface (E3)

The initially flat surface between the splitter and the curved surface, Zone 2, has a minor thickness reduction with bulging lines inclined outwards from the splitter (Fig. 3a). These bulging lines are formed by scratching and sliding sediment particles on the whole surface of Zone 2. The erosion conditions are similar for erosion type E3 and type E2 with the difference that the high radius of curvature in Zone 2 causes less separation of sediment particles from flow-streamlines. Erosion type E3 can be quantified with thickness loss and distance between bulging lines. The distance between these lines can be measured with a ruler; but templates are needed for measurement of thickness reduction.

3.4. Cavitation-erosion synergy near entry and bucket root (E4)

Due to surface irregularities giving rise to the secondary flows within the buckets and splashing water impinging on the buckets especially in multi jet Pelton turbines [21], pitting holes are created in front and rear parts of the buckets around Zone 2. Erosion type E4 is inclined radially outwards in the front part whereas radially inwards in the rear part (Fig. 3a). These pitting holes are small in size but large in numbers. The pitting effect may have started after erosion of splitter tip and distortion of splitter by erosion type E1. Erosion type E4 can be quantified with the diameter and number of holes as well as the length of the hole. The number can be counted in-situ and close photographs of surface with a simple ruler may provide the small holes size (diameter) and length.

3.5. Polished smooth surface with metallic lustre (E5)

During the operation of Pelton turbine, small droplets of water are formed around the entire runner periphery (Fig. 3b). Small sediment particles stay entrapped in these droplets and form an eroding atmosphere within the runner housing. Moreover, the presence of water droplets without sediment particles may also lead to drop erosion. These droplets polish the exposed areas leading to shiny surface with metallic lustre on the outer side of the bucket. Erosion type E5 leads to a smooth metallic surface and can be quantified with a reduction in thickness as well as roughness. The reduction in thickness can be
measured with templates and a roughness tester is required to measure the change in roughness.

3.6. Hydro-abrasive erosion in coated buckets

The erosion of coated surfaces depends on the bond of the coating with the surface material, the coating properties and the method of coating [22]. Due to the brittle nature of hard coatings, the coated buckets get mainly eroded in the splitter and cut-out with minor erosion in curved zone (Fig. 5). Major portions of the coating remain intact in curved zone till the significant erosion in the splitter and cut-out regions leads to overhauling of runner. The intact coating acts as reference for erosion measurement in coated buckets [6].

4. Methodology

During the study period from May to October 2015 (3180 h of turbine operation), the erosion was measured by the difference between the initially original and finally eroded states of buckets. The suspended sediment parameters were measured throughout the study period. The field study mainly comprises of two parts (a) erosion measurement in buckets and (b) suspended sediment measurement.

4.1. Erosion measurement with a 3D-scanner

A 3D-scanner (COMET L3D 1 M, Carl Zeiss), made of a light emitting diode (LED) and a camera, was used to measure the erosion of buckets. The light beam of the LED was focused on the bucket surface and observed with the camera positioned next to a position-resolving photodiode to scan the surface based on triangulation principle [23]. The system used has a resolution of one megapixel in a measurement volume of $92 \times 69 \times 60 \text{ mm}^3$. The 3D point distance is 79 µm and the accuracy of the system is within 8 µm. However, certain inaccuracies have crept in at various stages of the measurement process, such as the overlapping of scanned surfaces and uneven distribution of white spray used during measurement. Hence, the maximum deviations due to these factors may be assumed to lie in the range of 20–30 µm. Since the scanning procedure was time consuming, the study was restricted to scanning two buckets. The scanned images were analysed using Inspect Plus software which enabled superimposition of images with co-ordinate system shown in Fig. 6. The erosion depth, pattern and volume were obtained from superimposed images in both buckets. For erosion depth, the points were selected 1 mm apart along the initial surface for splitter top and curved section at PCD. In each division of both buckets (Fig. 1), total of 100 points (50 points for each bucket) were selected randomly and erosion depths were measured. Finally, the hydro-abrasive erosion inside the bucket was analysed as per the classification provided above.

In an attempt to visualise erosion outside the buckets, all the buckets of Pelton runner were painted from outside in Unit-1 at the time of installing new runner on 5th May 2015. To visualise the erosion initiation and pattern, images of painted buckets were obtained after 400 h (3 weeks) of turbine operation in low SSC inflow. Further, images
of the eroded buckets were obtained from close distance at the end of the study period to obtain and analyse erosion type E4. The images of coated buckets in Unit-2 were also obtained and analysed for the same study period of 3180 h of turbine operation from May to October 2015. The erosion in the curved portion of coated bucket, Zone 3, was measured with a ruler.

4.2. Suspended sediment measurement

The suspended sediment parameters, such as size, concentration, shape and mineral composition, affect erosion in buckets [6,8]. These parameters were measured from manual samples collected twice daily in the desilting tank as per IS 4890 [24] during the study period May to October 2015. Rai et al. [25] provided the details of the methodology for collection and for SSC measurements using gravimetric method as per IS 6339 [26]. To calculate the suspended sediment load (SSL) (in tonnes), the obtained values of SSC were used with flow rate in Eq. (1).

\[
SSL = \frac{SSC \times Q \times \Delta t}{10^6}
\]

where SSC is the suspended sediment concentration in parts per million (ppm) by mass, \( \Delta t \) is the time in seconds and Q is the discharge in m\(^3\)/s.

For a period of 9 weeks from 29 May to 6 August 2015, a multi-frequency backscatter acoustic device (SediScat, HydroVision) was used to measure SSC and PSD continuously, detailed in [25]. To find the feasibility of using two most commonly used methods to measure suspended sediment parameters continuously, turbidity and laser
Diffraction sensors were used on manually collected samples in the laboratory. The collected samples were analysed with a turbidimeter (2100 P Portable, Hach) to measure SSC and with a laser diffraction instrument (LISST - Portable, Sequoia) to measure PSD as well as volumetric SSC. The PSD and shape distributions were obtained from a dynamic imaging based instrument (Camsizer XT, Retsch) for 200 samples throughout study period. The mineral content of the sediment was determined using powdered X-ray diffraction (XRD) analysis and quantified with petrography analysis for 5 samples.

Suspended sediment parameters such as median size ($d_{50}$), SSC, SSL and shape were non-dimensionalised using Eq. (2).

$$X_{scaled} = \frac{X}{X_{max}}$$

where $X_{scaled}$ is a non-dimensional quantity, $X$ is the suspended sediment parameter at any specific time and $X_{max}$ is the maximum value of the same parameter during the entire study period. To measure the variation in parameters of erosion depth and suspended sediment, the coefficient of variation (CoV) was calculated as per Eqs. (3)–(5).

$$C_{\text{uv}} = \left( \frac{s_{uv}}{\bar{X}} \right) \times 100\%$$

$$s_{uv} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{X})^2}$$

Fig. 9. Hydro-abrasive erosion in (a) uncoated bucket parts, (b) curved portion (c) splitter portion with erosion depth colour scale in mm and (d) erosion depth in the cut-out in mm.

Fig. 10. Variation of erosion depth along the bucket surface at the PCD plane parallel to YZ plane in two uncoated Pelton buckets.
\[ \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \]  

(5)

where \( C_{\text{xx}} \) is the CoV for parameter \( x \), \( s_x \) is the standard deviation, \( \bar{x} \) is the mean of same parameter \( x \) and \( n \) is the number of values obtained during study period.

5. Results and discussions

5.1. Hydro-abrasive erosion of Pelton buckets

The amount of material removed and erosion depth showed significant variation along entire surface of both buckets; however, these were symmetric with respect to the splitter (Fig. 7).

5.1.1. Hydro-abrasive erosion inside the bucket

Rai et al. [19] analysed the erosion inside buckets from the consideration of separating forces on suspended sediment particles. Due to the highest separation angle of sediment particles from flowstreamlines as well as near-wall SSC, the outer portion inside bucket was found to be most prone to erosion. However, a circular bucket profile was considered for simplicity in a plane of constant radius of rotation from the runner axis. Brekke et al. [5] hypothesized that the inside bucket section with the least radius of curvature in the bottom portion is most prone to erosion. As the studied buckets had the minimum value of radius of curvature in Zone 3, the maximum amount of erosion was found in Zone 3 (Fig. 7b and c).

The erosion in buckets is analysed and presented in four parts (a) splitter and cut-out region, (b) curved region, (c) outside region and (d) erosion type E3 and E4.

5.1.1.1. Hydro-abrasive erosion in the splitter and cut-out region inside buckets

The erosion caused the reduction in height (\( \Delta h \)) and the increase in width (\( \Delta b \)) of the splitter top of both investigated buckets (Fig. 8a). The initial bucket tip was completely eroded and a conical tip was formed around 10 mm radially inwards (Fig. 8a and b). Due to this conical tip, the sudden variations in \( \Delta h \) and \( \Delta b \) curves were obtained as marked in Fig. 8a. The increase in splitter width for both buckets was similar. However, the reduction in height between the eroded bucket 1 (EB1) and eroded bucket 2 (EB2) varied by approximately 2 mm. The ripples in the curves, erosion type E1, had variable wavelength along the splitter with an average value of 15–20 mm (Fig. 8a-c). The maximum values of \( \Delta b \) and \( \Delta h \) were found near the PCD and radially outwards from the PCD respectively. Due to the increase in splitter

![Fig. 11. Inception of erosion in (a) a coated Pelton bucket and (b) outside Pelton bucket.](image1)

![Fig. 12. Change in outflow direction due to erosion within the Pelton bucket.](image2)

![Fig. 13. Pitting phenomenon in uncoated Pelton buckets.](image3)
width, efficiency of the Pelton runner decreased. At full load, an increase of Δb by 1% of the inner bucket width resulted in approximately 1% efficiency drop [5]. The amount of material lost was 72.24 cm³ from the portion of the bucket shown in Fig. 9a and c.

The erosion depth in the cut-out region of the bucket (Δc) varied considerably; but, the pattern was symmetric on both sides of bucket tip (Fig. 9d) with respect to the splitter. The value of Δc increased from the bucket tip to middle of the cut-out in both halves of the buckets and decreased to a minimum at the end of the cut-out. This pattern could be attributed to the interaction of the jet within the cut-out. Due to erosion in the cut-out (Δc), the effective outer diameter of the Pelton runner was reduced by 2% of the initial value. This reduction would delay the entry of the water jet in each bucket by (T₁ - ET₁) and results in an exit at an earlier instant in time (ET₆ - T₆) (Fig. 4). As an effect, the water cycle of jet in each bucket would reduce leading to less shaft torque produced and a drop in efficiency of the turbine.

The maximum values of erosion depth were 19.8 mm and 12.9 mm in the cut-out and splitter portion respectively for uncoated bucket. The

### Table 1

Erosion depth in uncoated Pelton buckets.

<table>
<thead>
<tr>
<th>Erosion type</th>
<th>Affected zone of bucket</th>
<th>Erosion depth (mm)</th>
<th>Co-efficient of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>Splitter zone inside bucket</td>
<td>Front 12.22 10.46</td>
<td>5.26 3.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle 14.94 13.04</td>
<td>12.71 10.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rear 12.82 11.03</td>
<td>7.19 2.72</td>
</tr>
<tr>
<td>E2</td>
<td>Curved zone inside bucket</td>
<td>Front 7.95 6.60</td>
<td>0.63 0.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle 5.64 5.63</td>
<td>0.59 0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rear 5.90 6.25</td>
<td>1.85 0.98</td>
</tr>
<tr>
<td>E3</td>
<td>Between splitter and curved zone inside bucket</td>
<td>Front 2.36 2.85</td>
<td>0.10 0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle 1.48 2.63</td>
<td>0.43 0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rear 2.90 3.02</td>
<td>0.15 0.16</td>
</tr>
<tr>
<td>E4</td>
<td>Inside bucket</td>
<td>EL (Fig. 13) 14.61</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ED (Fig. 13) 0.95</td>
<td>0.30</td>
</tr>
<tr>
<td>E5</td>
<td>Outside bucket</td>
<td>All parts 0.97 1.42</td>
<td>0.21 0.01</td>
</tr>
</tbody>
</table>

### Table 2

Average presence of particles in different size classes.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Size class (μm)</th>
<th>Average range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0–3.9</td>
<td>5.0</td>
</tr>
<tr>
<td>Silt</td>
<td>3.9–62.5</td>
<td>72.9</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>62.5–125</td>
<td>12.3</td>
</tr>
<tr>
<td>Fine sand</td>
<td>125–250</td>
<td>8.3</td>
</tr>
<tr>
<td>Medium sand</td>
<td>250–500</td>
<td>1.6</td>
</tr>
</tbody>
</table>

### Fig. 14

Size distribution of particles passing through turbines.

### Fig. 15

Variations in suspended sediment properties during the study period.
average reduction in splitter height and cut-out section was 3% and 5% of the bucket width in uncoated buckets. In the splitter and cut-out of coated buckets, the erosion (∆h and ∆c) could not be measured due to non-availability of templates at the study site.

5.1.1.2. Hydro-abrasive erosion in the curved portion inside the bucket

In a cross section at the PCD, the variation of erosion depth displayed erosion type E1, E2 and E3 along the inside surface of both buckets (Fig. 10). In Zone 3 inside the bucket, the ripple erosion Type E2 had the maximum erosion depth near outlet with values in range of 3–5.5 mm at the PCD section. For erosion type E2, the ripples had wavelength values in the range of 15–30 mm and 12–14 mm along bucket outlet (∆Bo) and along radial directions (∆Br) respectively (Fig. 9b). The erosion type E1, shown as sharp variation in erosion depth plot (Fig. 10), caused erosion depths of 15 mm in the splitter of bucket 1 (B1) and 13 mm in bucket 2 (B2) at the PCD. At the PCD, the erosion type E3 showed an almost flat erosion pattern and the erosion depth was in the range 1–1.5 mm, which was less compared to E1 and E2.

The coated buckets in Unit-2 had significant erosion of the base material in some parts of Zone 3 and no erosion in other curved portions (Fig. 11a). The coating protected the bucket profile even after the whole season with minor erosion around 1.5 mm in some patches of the curved region. In Zone 3 inside the bucket, the location of maximum erosion depth was similar in coated and uncoated buckets (Fig. 7b, c and Fig. 11a). This finding was due to the fact that the profile and the erosive conditions for both coated and uncoated buckets were the same during the study period. Protecting this part of Zone 3 with a thick coating may reduce erosion damages of the base material.

5.1.2. Hydro-abrasive erosion outside the buckets

Due to erosion inside the bucket, the initially smooth bucket profile at outlet deformed to a rippled surface. This change in profile led to a flow towards the backside lateral portion of the adjacent bucket (Fig. 12). At the outside bucket surface of Zone 3, the erosion was caused by this flow change from the inner bucket profile [27]. Due to a higher amount of water hitting the backside at full load, the efficiency drop of eroded buckets was higher at full load compared to part load [27]. Moreover, the ventilation in the housing led to splashing water impinging on the backside and with plenty of sediment ventilating around, the whole outer side of the bucket developed erosion type E5 with increased exposure time (Fig. 11b). The erosion outside the bucket was significantly less with a maximum erosion depth of the order of 1.0 mm (Fig. 7d).

5.1.3. Analysis of erosion type E3 and E4 inside buckets

The synergy of cavitation, material casting defect as well as hydro-abrasive erosion could have created the pitting phenomenon inside buckets (Fig. 13). The presence of material casting defect might have initiated cavitation in the wake of these defects. The rough surface arising from cavitation was afterwards smoothed by hydro-abrasive erosion. Once the casting defect is partially removed by hydro-abrasive erosion, cavitation is reduced or disappears and the rough surface arising from the cavitation is smoothed by hydro-abrasive erosion. These processes could have led to the observed eroded pitting holes and the traces of the wake, shaped like a tadpole.

IEC [28] describes the major parts of the buckets susceptible to cavitation as (a) front part of Zone 1, (b) middle part of Zone 2 and Zone 3 along with (c) back part of the splitter and the cut-out. The pitting observed in the front part of Zone 1 is in agreement with IEC [28], whereas it is not so in the rear part of Zone 2. The pitting holes, erosion type E4, had erosion diameter (ED) between 0.3–0.5 mm and erosion length (EL) of 8–12 mm, measured from scanned images (Fig. 13a - d). Similar pitting holes were also reported in the bucket shown in Fig. 13e [10] and a small specimen of a Francis blade [9]. The bulging lines, erosion type E3, were around 20–30 mm apart as measured from scanned images of buckets (Fig. 13a and c).

The maximum, minimum and average values of erosion depth of various erosion classes along with the coefficient of variation for both uncoated buckets are provided in Table 1. The difference between average values of both buckets indicates that erosion type E1 showed significant variations in both buckets, though they faced similar erosion conditions. 50 points were measured for each type of erosion in both the buckets in the respective zones.

5.2. Suspended sediment analysis

For erosion, the vital suspended sediment parameters such as SSC, PSD, SSL, shape and mineral content were measured and analysed in this study. The variations of these parameters were assessed to find a suitable technique to measure and to cope with mitigating erosion. The possibility of using turbidity and laser diffraction instruments for online measurement were also explored. A methodology is discussed for quantifying the shape of suspended sediment based on sphericity and b/l ratio. The suspended sediment analysis is presented in four parts as (a) PSD, (b) SSC and SSL, (c) shape as well as (d) mineral content and Figure 17. Size and shape distribution of a sample.
5.2.2. SSC and SSL measurement

The maximum values of SSC and SSL passed through each turbine during turbine operation of 3180 h were 1374.3 mg/l and 12,540 t respectively. The major portion of suspended sediment, approximately two third, passed in 1200 h of turbine operation, during July to August the peak period of monsoon. This type of suspended sediment variation with high flows during a few days of high rainfall is common [1,4,12]. 20% of the SSL passed during a period of only 10 days of high SSC flow equivalent to 7% of the turbine operation. The erosion can be mitigated economically by managing the plant operation during these days of high SSC flow with detailed analysis of (a) cost of repair and replacement, (b) energy loss due to downtime and efficiency decrease, and (c) cost of inventory and safety measures. The coefficient of variance obtained for SSC and SSL (weekly) were 75% and 65% respectively.

5.2.3. Suspended sediment shape

In water sample with suspended sediment from natural environment, the shape of particles differs from each other which results in a shape distribution curve. The nature of this curve was S-shaped for the study site, similar to PSD (Fig. 17). The particles with sphericity greater than 0.9, 0.9 to 0.6 and less than 0.6 are nearly spherical, angular and elongated respectively. The median values of shape parameters, sphericity and b/l ratio, were obtained similar to d50 value for size in PSD.

During high SSC flow between mid-July to end-August, d90 values were higher than 250 µm occasionally (Fig. 14). This confirmed proper working of desilting chamber of the plant. The coefficient of variance obtained for d10, d50 and d90 were between 25% and 32%.

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5.2.4. Mineral content of sediment from study site using petrography analysis

The PSD measured with dynamic imaging (Camsizer) and laser diffraction (LISSST) instruments showed similar values for d10, d50 and d90 (Fig. 14). The value d9 represents particle sizes under x% of particles in the PSD of a sample. Throughout the study period, the values of d10, d50 and d90 were in the range of 5–10 µm, 20–40 µm and 80–160 µm respectively (Fig. 14). This confirmed proper working of desilting chamber of the plant. The coefficient of variance obtained for d10, d50 and d90 were between 25% and 32%.

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5.2.5. Suspended sediment parameter variation

The maximum values of SSC and SSL passed through each turbine during turbine operation of 3180 h were 1374.3 mg/l and 12,540 t respectively. The major portion of suspended sediment, approximately two third, passed in 1200 h of turbine operation, during July to August the peak period of monsoon. This type of suspended sediment variation with high flows during a few days of high rainfall is common [1,4,12]. 20% of the SSL passed during a period of only 10 days of high SSC flow equivalent to 7% of the turbine operation. The erosion can be mitigated economically by managing the plant operation during these days of high SSC flow with detailed analysis of (a) cost of repair and replacement, (b) energy loss due to downtime and efficiency decrease, and (c) cost of inventory and safety measures. The coefficient of variance obtained for SSC and SSL (weekly) were 75% and 65% respectively.

The multi-frequency acoustic sensor, installed at the study site, was able to capture correct SSC values initially but stopped working after 6th August detailed in [25]. A good relation obtained between SSC and turbidity (R² = 0.90) from 231 samples (Fig. 16), indicated the suitability of an online turbidimeter for continuous SSC monitoring at the study site. The linear relationship between SSC and turbidity with high value of the correlation co-efficient (R²) is reported frequently in literature [30–33]. However, turbidity depends significantly on suspended sediment parameters variation [33], which limits its use to small watersheds with less variation in suspended sediment parameters [34].

The laser diffraction instrument in the laboratory was found more suitable for erosion study as better relation (R² = 0.91) between SSC and LISSST SSC (volumetric) was obtained from 124 samples (Fig. 16). In addition to volumetric SSC, the laser diffraction instrument provided PSD for study site (Fig. 14). For the conversion of volume concentration (μl/l) to mass SSC (mg/l), density of suspended sediment (around 2.65 kg/m³) is required. In this study, volumetric SSC readings were close to actual mass SSC without this conversion. This may be attributed to the fact that LISSST readings deviate significantly for irregularly shaped particles [35]. To convert measured turbidity and laser diffraction readings continuously to mass SSC (g/l), a field calibration curve was determined for the study site (Fig. 16). This approach is used by researchers in literature [25,35].

5.2.6. SSC and SSL measurement

The maximum values of SSC and SSL passed through each turbine during turbine operation of 3180 h were 1374.3 mg/l and 12,540 t respectively. The major portion of suspended sediment, approximately two third, passed in 1200 h of turbine operation, during July to August the peak period of monsoon. This type of suspended sediment variation with high flows during a few days of high rainfall is common [1,4,12]. 20% of the SSL passed during a period of only 10 days of high SSC flow equivalent to 7% of the turbine operation. The erosion can be mitigated economically by managing the plant operation during these days of high SSC flow with detailed analysis of (a) cost of repair and replacement, (b) energy loss due to downtime and efficiency decrease, and (c) cost of inventory and safety measures. The coefficient of variance obtained for SSC and SSL (weekly) were 75% and 65% respectively.

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values of 0.837 and 0.738 respectively. The maximum, minimum and average values of suspended sediment parameters along with coefficient of variation throughout study period are provided in Table 3.

5.2.4. Mineral content and hardness

The mineral content of sediment particles were identified in the laboratory using X-ray diffraction analysis and quantified with petrography analysis. The hardness of the particles was assigned from petrographic literature. The Mohs scale, a non-linear scale introduced in 1812, is commonly used for sediment mineral hardness [36]. The scale ranges from 1 (chalk) to 10 (diamond). The analysis of sediment from the study site is presented in Table 4 and Fig. 18.

The buckets of the study plant were made of martensitic stainless steel with 13% chrome and 4% nickel composition (13Cr4Ni). The buckets of Unit-2 were coated with tungsten carbide, cobalt and chrome (WC-Co-Cr) coating of 300 ± 50 μm thickness applied by High Velocity Ox Y Fuel (HVOF) method. The 13Cr4Ni martensitic steel has a Mohs hardness of ~4.5 [6], which is softer than quartz and feldspar particles with Mohs hardness 7 and 6 respectively. WC-Co-Cr coatings have Mohs hardness varying from 6.5 to 7, a value similar as quartz [36].

6. Conclusion

The hydro-abrasive erosion in Pelton buckets of Toss HPP (10 MW), located in the Indian Himalayas, have been studied from May to October 2015 during 3180 h of turbine operation. Based on the analysis of eroded buckets from literature and the study site, hydro-abrasive erosion has been classified and methods have been proposed to measure them. The hydro-abrasive erosion was measured with an optical 3D-scanner and suspended sediment parameters were obtained with gravimetric, turbidity, laser diffraction and dynamic imaging techniques. The main conclusions from this study are as follows.

1. The hydro-abrasive erosion in buckets was classified in 5 different types – i) wave erosion of the splitter (E1), ii) ripple erosion in the curved surface inside of buckets (E2), iii) bulging/protruded erosion lines between the splitter and the curved surface inside buckets (E3), iv) cavitation-erosion synergy near the entry and in the bucket root (E4) and v) polished smooth surfaces with metallic lustre outside of buckets (E5). Detailed measurement of each type has been presented and discussed. Erosion in coated buckets was also measured for same duration in the same plant.

2. 3D-scanning has been found to have distinct advantage over other methods of hydro-abrasive erosion measurement as it allows to measure depth, profile as well as material loss. The decrease of splitter height, increase of erosion depth in curved zones and abrasion in the cut-out portion were averagely 3%, 1.5% and 5% of the bucket width. Erosion depth in the curved zone of coated buckets was around 1.5 mm in a few patches while the coating remained intact in other parts.

3. The erosion of the surface inside buckets had directed the flow towards the lateral surface of the outside of the successive bucket. The erosion of the outside surface of bucket was considerably lesser than on the inside surface.

4. The sediment properties like concentration and size have been found to vary significantly during the monsoon/rainy season. It is recommended to measure these vital properties with continuous monitoring instruments to capture the high sediment load events, which are otherwise likely to be missed out.

5. Sediment shape has been quantified with respect to sphericity and aspect ratio. These factors have been found to vary within a narrow range establishing the common notion that shapes of particles vary less due to their origin from the same catchment.

Bypassing the high sediment load events will save the turbine from erosion. However, a detailed financial analysis is required for the same.

In this article, the hydro-abrasive erosion has been dealt from flow aspects discussed in the classification section. Further work from the microstructure aspect will add to the understanding of the erosion mechanism for both coating and uncoated material. This study provides information to turbine designers, manufacturers and hydropower plant managers to decide the location of areas prone to erosion where coating is required in case of erosion and to design erosion friendly turbine buckets.

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