Analysis and visualization of progressive erosion in Pelton buckets

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Abstract. Hydropower plants operating in fragile mountainous regions face severe hydro-abrasive erosion of hydraulic components, which results in drop in efficiency, frequent interruptions in power generation and downtime for repair/replacement. Due to high flow velocity in components like nozzles and buckets, a Pelton turbine is highly susceptible to erosion. The effect of erosion is observed as cumulative loss of material and study of its gradual progress required frequent measurement. In this study, in-situ images of Pelton buckets were captured throughout a sediment period at a hydropower plant located in Himalayan region, India and analysed for characteristics of progressive erosion damages. A multi-layered paint method was used to visualize the initiation of erosion in different parts of bucket. Removal of colours due to erosion provided the information on erosion initiation and various erosion zones in bucket. The erosion of outer side of bucket was analysed with single layer paint removal and images from past records of the plant. Further, the effect of initial condition of a bucket on cumulative erosion after a sediment season is also presented for both coated and uncoated buckets.

The in-situ photographs during the silted water period suggested that the outlet portion inside the bucket faces significant erosion. The technique of image capturing throughout sediment season was successful in obtaining progressive erosion. Such method with a reference scale in the image is an effective method to quantify erosion like width increase of the splitter more frequently. The paint in the buckets was found capable of providing information on erosion initiation and erosion zones inside Pelton buckets. The erosion characteristics of outer side of the bucket confirms the presence of a Coanda effect. This study will facilitate turbine designers and manufacturers in better coating and/or surface treatment to specific zones of bucket to minimize efficiency loss due to distorted profile of the bucket, as more prone surfaces can be coated with thicker coatings to protect it longer from erosion.

Keywords: Pelton, Bucket, Erosion, Sediment, Efficiency, Hydropower.
1. Introduction

Most of the streams in geologically young mountains, like the Andes and the Himalaya, contain high sediment concentration during the rainy/monsoon seasons. This incoming sediment with water causes hydro-abrasive erosion of hydraulic turbines and components coming in contact. The problem of hydro-abrasive erosion possesses challenges in the smooth and efficient operation of existing hydropower plants (HPP) as well as in development of new hydropower plants in these regions. Recently, erosion is becoming more severe problem because worldwide focus is high on promoting renewable, non-fossil energy resources and high energy demand requires high machine efficiencies. Erosion changes the profile of the turbine blades/buckets, which plays major role in efficiency of the turbine, finally leading to power generation loss. Run-of-river plants face high erosion as no storage for sediment settling is available. Due to high head, even small sediment particles cause acute hydro-abrasive problems in Pelton turbines. Though researchers have identified parameters involved in erosion in Pelton turbine like sediment concentration, size, material composition, erosion velocity [1-3]; the quantitative information of influence of these parameters is not known fully. IEC 62364 [3] presented an empirical model for erosion calculation in hydro-turbines; however, the values of model co-efficient related to Pelton turbine were not provided due to lack of field studies of erosion in Pelton turbines.

Bajracharya et al. [4] studied Pelton turbine erosion in 22 MW Chilime HPP in Nepal to relate erosive wear rate and efficiency reduction. Erosion of needle and spear rings was measured with a stylus probe whereas sediment was examined with sieves and mineral analysis in laboratory. Erosion depth of 3.4 mm/year, which resulted in loss of 1.21% efficiency of turbine, was mainly caused by high sediment load with presence of hard minerals. Boes [5] studied erosion in Pelton turbine of Dorferbach HPP from May to October 2008 by – (1) erosion - measuring increase in splitter width (total 17 times for 3 Pelton wheels) and (2) sediment – measuring concentration and PSD using an optical backscattered turbidimeter and a laser diffraction instrument continuously along with manual pumped sampling. An erosion model for the plant was developed. In studies in actual power plants, researchers usually measure erosion by thickness loss with help of templates [6]. Felix [7] measured erosion of Pelton turbine buckets by 3D-digitization with an optical scanner of 515 m high head 2×32 MW Fieschertal HPP from 2012 to 2014. The sediment concentration and size were measured with turbidimeters, acoustic and laser diffraction instruments continuously during the study period. Significant erosion was obtained only in 2012 due to a major sediment event. In all these erosion studies, researchers have obtained/quantified/analysed the erosion at initial and final stage of erosion only which is not sufficient to provide progressive erosion information. Though Boes [5] measured progressive erosion, the study only limited its scope to erosion width of splitter.

The stepwise progressive erosion is generally not measured in power plants because of time, equipment and skill requirements and energy generation loss during measurement. In laboratory study, the progressive erosion of test specimen is usually measured with weight loss [8-9] which is not capable of providing profile changes and erosion initiation information. The major drawback in laboratory studies, which took small impulse turbine buckets [9-10], is the use of soft material brass and high sediment concentration for getting substantial amount of erosion in short time. Rajkarnikar et al. [11] used paint method on small Francis blades to visualize erosion in laboratory. In numerical studies, it is possible to observe the progressive loss of erosion; however, the flow in Pelton bucket has been studied numerically and experimentally [12-14], but without particles. Solid particle erosion in Pelton buckets has not been numerically simulated so far. Moreover, the verification of progressive loss of material in numerical study will require actual studies for verification.

In this study, two adjacent Pelton buckets of a hydropower plant in Himalayan region of India were completely painted with layers of 3 colors to visualize and classify the erosion in Pelton buckets. In another attempt, the outer sides of all the buckets were painted and erosion behavior of bucket from outside was analyzed. Further, a simple technique which involved taking images of eroded Pelton buckets during shutdowns/downtime throughout the monsoon period and analyzing these images at the end of monsoon/rainy season to get crucial information like initiation of erosion and progressive
erosion during the period of study is presented. This information will allow mitigating erosion by thicker coating or heat treatment of specific location of the buckets. The time required to capture image during this study was very less (few minutes) and did not involve generation loss as it was performed during shutdowns/outages. The sediment concentration and size was measured with an acoustic instrument continuously and twice daily manual samples collected throughout the study period.

2. Case study
The study site Toss HPP with 10 MW capacity is a located in Himalayan range i.e., 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 m$^3$/s. The desilting tank with forebay of the plant is designed to remove sediment particle size greater than 200 microns. The initial inspection of Toss HPP during planning stage of erosion study revealed that the plant was severely affected by erosion since its commissioning in 2008-09. The uncoated Pelton turbines installed in the plant were extensively eroded and required replacement after one/two years of operation.

3. Case study
The study comprises of mainly four parts, namely erosion zone identification with different colored paint layers (paint removal) inside Pelton bucket, progressive erosion from outside of bucket, erosion measurement with photographs at different intervals throughout monsoon period and sediment load/size measurement. The methods involved in all these four parts were different and presented in following subsections.

3.1. Erosion visualization and classification in zones inside Pelton bucket with paint layers
In Toss HPP in Himalayan region of India with erosion issues, two adjacent buckets of a new uncoated Pelton wheel were painted completely from both inside and outside in layers of 3 different colors green, yellow and red as shown in Fig. 1. Spray paint was evenly applied all over the buckets to get uniform thick layer of the paints. The Pelton wheel with painted buckets was installed and operated for two days in silty water and then the plant was stopped to observe the effects of silt on removal of paints. Different colors were used to visualize progressive erosion in different parts of the bucket for classifying erosion zones in bucket.

![Figure 1: A Pelton bucket colored in 3 different layers](image)

3.2. Erosion in outside of bucket
In another attempt to visualize erosion, all the buckets of a Pelton wheel at the Toss HPP were painted from outside and the wheel was installed. The Pelton wheel was operated in sediment laden water for 3 weeks during low sediment transport time. Images were taken at each stage i.e., after colouring outside initially and after 3 weeks of operation. Again, the same Pelton wheel was operated for power generation throughout the monsoon season and images were obtained at different time interval. The images of the eroded Pelton buckets from past/historical records of the plant were used along with the
images recorded throughout the monsoon season to (get the insight of) analyze the stepwise progressive erosion of the bucket, especially from outer side. As the bucket profile was same during the past, the obtained results are expected to be reasonably accurate.

3.3. Erosion measurement with images at different interval of time
The images of the eroded Pelton buckets were taken from inside throughout the monsoon season to observe the stepwise progressive erosion. The term stepwise progressive erosion is defined as the gradual cumulative process of erosion. This process of image capturing was expected to reveal the stepwise erosion process inside a Pelton bucket. The images of the bucket were obtained mainly during the shutdowns to avoid energy generation loss during the study. Further, very close images of the buckets were obtained after the end of monsoon season to analyse/obtain erosion effect at micro-level. This was expected to provide information about presence of cavitation phenomenon or material defect. The erosion images of another Pelton wheel with coated buckets were also obtained and analysed.

3.4. Sediment measurement
The properties of sediment such as size, concentration, shape and mineral composition play major role in erosion [1,3]. Shape and mineral composition of sediment at a site do not vary much; hence, these values computed at reasonable span of time interval is sufficient for erosion study [3]. However, size and concentration of the sediment particles vary a lot in very short span of time; thus these parameters require continuous or frequent monitoring. Though the instruments for monitoring sediment concentration and size continuously are available [15], its use is not common due to limitations of measurement in varying field conditions.

The methodology adopted for size and concentration measurements of sediment transport at Toss HPP are provided in Rai et al. [6]. A continuous acoustic device for a period of 9 weeks and twice daily manual samples throughout the monsoon/study period of 23 weeks were obtained. The obtained values were used along with flow data to calculate the sediment load passing through the turbine for a specific interval of time during monsoon season. The sediment load (SL) in tonnes in a time interval was calculated as given in Eqn. (1).

\[ SL = \frac{SSC \cdot Q \cdot t}{10^6} \]  

where SSC is suspended sediment concentration in parts per million (ppm) by mass and Q is discharge in m$^3$/s in total time t.

4. Results and discussions

4.1. Erosion zone identification with paint removal
The observation of two adjacent Pelton buckets coloured in 3 layers revealed that the paint from the bottom portion of the bucket was completely removed as shown in Fig. 2. This confirms that the bottom of the Pelton bucket is most severely affected due to erosion and the erosion process starts from there (initiation of erosion).

Figure 2: Erosion of layers of paint in different parts of Pelton bucket
Rai et al. [16] analysed the erosion phenomenon in Pelton bucket from force perspective and concluded that the outer portion of the bucket is most prone to erosion due to highest separating forces on sediment particles there. The reason for this theoretical finding was higher magnitude of separation forces at outlet resulting in greater separation angle and higher concentration of sediment particles. However, they considered circular profile for simplicity having constant radius of curvature. In actual case with Toss HPP Pelton bucket, the profile was made of varying radius of curvature having minimum value at the bottom portion. The respective magnitudes of radius of curvature in different zones of the bucket are shown in Fig. 3. Due to the least radius of curvature at bottom portion, the highest effects of erosion were observed at bottom portion with complete removal of 3 layers of paints. Brekke [17] also observed that the bottom portion of Pelton bucket suffers highest erosion due to smallest radius of curvature in this portion of the bucket.

![Figure 3: Various radius of curvatures in Pelton bucket profile of Toss HPP](image)

The outer zone with removal of 1 layer of paint (Fig. 2) had higher magnitude of eroding forces due to lower radius of curvature compared to the inlet zone of the bucket (Fig. 3). Hence, the outer zone observed higher erosion with respect to the inlet portion which showed no sign of erosion. The finding from this study can be used to classify the Pelton bucket into 3 zones as shown in Fig. 4. Rai et al. [6] also classified the Pelton bucket into 3 zones; however, the classification in this study in more realistic/applicable as an actual Pelton bucket profile is considered.

4.2. Erosion in outside of the bucket

The progressive loss of paint from outer side of the bucket is provided in Fig 5a-5c. The removal of paint from outer side was mainly in the opposite side of zone 3. This erosion was caused by the sediment laden water leaving the bucket where water flows after the current bucket to pass over the backside of bucket ahead. The erosion of bucket from backside due to this water increased with increase of operating hours of Pelton wheel and finally led to complete material removal from zone 3 (Fig. 5d-5g). From past records of the Toss HPP, the process of material removal started with a hole on this side which gradually grew and resulted in complete removal of the material making the wheel unrepairable. Though the material removal process started from zone 2 defined above, the bucket material from zone 3 got completely removed first due to two reasons:

i. Both erosion from bucket inside and outside leading to more resultant erosion (erosion from backside was not present in zone 2)

ii. Higher thickness of material in zone 2 compared to zone 3

Once the material is completely removed, the efficiency of the Pelton wheel reduces considerably due to loss of water without doing complete work inside the bucket and creates undesired turbulence inside the bucket flow. Moreover, this may also lead to higher erosion rate from this stage onwards and leads to an eroded wheel which is unrepairable through simple techniques like welding as shown in Fig. 5f-5g.
4.3. Erosion analysis through images/photographs throughout monsoon period

The progressive erosion of inside portion of tested Pelton buckets with respect to time is shown in Fig 6a-6h. The scaly erosion observed was similar to the erosion pattern described in literature [18]. Fig. 6a shows a new Pelton bucket with finishing/grinding/polishing marks on it. After running/operating the wheel for a period of 3 weeks in low sediment water, the bucket surface got smoother w.r.t. the initial condition and finishing marks were removed (Fig. 6b). High sediment load after that till mid-July in the monsoon/rainy season initiated/started significant erosion inside Pelton buckets in middle portion of zone 3 and back portion of zone 1 as marked in Fig 6c and 6d. However, the erosion in zone 3 was greater than zone 1. The erosion in these specific portions of the bucket may be attributed to the flow direction of water in buckets. The flow is sideways during full jet flow on the splitter affecting middle-zone 3 whereas lengthwise from front to back at entry of jet in bucket affecting back-zone 1 [12,19].

With average sediment concentration/load rising in the next 2 weeks, the erosion spread to the full zone 3 and extended to zone 2 as well (Fig. 6e). The splitter tip and cut-out of the bucket was not affected considerably till now, though a minor effect was visible in the middle portion of splitter (Fig. 6e). The next 5 weeks also observed high sediment load resulting in increase of erosion depth and distortion of bucket profile (Fig. 6f). Noticeable/significant erosion was visible in zone 2 and well as splitter portion. The sediment load decreased during next 3 weeks; however, the erosion/distortion of bucket profile kept increasing and whole portion of zone 2 and zone 3 were affected severely (Fig. 6g). During recession period of average sediment concentration i.e., next 4 weeks till mid-October, the thickness of blades/bucket at outlet and zone 3 start reducing sharply. The splitter portion of the bucket also suffered/observed extreme erosion during this period. The cut-out portion of the bucket observed erosion mainly during peak sediment season i.e., in the duration 25th July – 14th September 2015.

A Pelton wheel with coated buckets installed in another unit of Toss HPP was also studied. As evident from Fig. 7, significant erosion was present in the middle portion of zone 2 and zone 3 with minor erosion in front portion of zone 1 after operating in water with sediment. This confirms the finding about initiation of erosion inside the Pelton bucket. While coating the Pelton buckets, zone 2 and zone 3 of the buckets require special attention and a thicker layer of coating in these zones in middle portion will increase the time between overhaul of turbine. Moreover, a reduction of curvature...
in zone 2 will reduce erosion effect in this zone and its subsequent effect on erosion in zone 3. A careful informed application of coating over the inner bucket surface will reduce erosion and plant can be operated for a longer duration without significant loss of energy generation due to reduced efficiency of turbine.

![Figure 6: Progressive erosion of Pelton bucket from May-October 2015 (W is Week from start)](image)

Figure 6: Progressive erosion of Pelton bucket from May-October 2015 (W is Week from start)

![Figure 7: Erosion initiation in a coated Pelton bucket](image)

Figure 7: Erosion initiation in a coated Pelton bucket

![Figure 8: Pitting phenomenon in Pelton buckets at micro-level](image)

Figure 8: Pitting phenomenon in Pelton buckets at micro-level

An interesting observation in Pelton bucket image was the presence of pitting phenomenon as shown in Fig. 8. The presence of cavitation or material casting defect along with erosion may be the reason for this pitting. IEC 60609-2 [20] presented zone 1-front portion, middle portion of zone 2 and zone 3, back of splitter and back of cut-out as the major portions of the Pelton bucket susceptible to cavitation. The pitting was observed on mainly zone 1-front portion which agrees with cavitation prediction of IEC 60609-2 [20]; however, the pitting in back portion of zone 2 was not in agreement with the standard. Rajkarnikar et al. [11] also observed similar pitting holes in small specimen of Francis blade due to cavitation and material casting defect.

4.4. Sediment measurement

The sediment parameters measured during study period are provided Table 1. The maximum and minimum values of sediment concentration and size found during study indicated the variation in these parameters with respect to time. The total load passed through the turbine was as high as 12,825 tonnes. The maximum sediment concentration recorded during the study was 1,374 mg/l. From the variation of sediment concentration and load as shown in Fig. 9, a step rise of average concentration is evident from mid-July which lasted upto mid-September. The average sediment concentration during
this 10 weeks period was high and resulted in 65% of sediment load. Controlling/routing major sediment events during this period would have reduced erosion. However, the decision of closing power plant require in depth study of financial implications of erosion and its effect.

Table 1: Sediment concentration, load and size variation during study period

| Time in week (W) | Sediment concentration in mass ppm (mg/l) | Sediment load in tonnes | Median size of sediment (d50) in micron m |
|------------------|------------------------------------------|-------------------------|-----------------------------------------|
|                  | Since last inspection | Since installation | min | max | avg | Since last inspection | Since installation | min | max | avg |
| 0                | 0                        | 0                        | 0   | 0   | 0   | 0                        | 0                        | 0   | 0   | 0   |
| 3                | 3                        | 88                       | 288 | 167 | 812 | 812                       | 26                       | 65 | 36 |
| 7                | 10                       | 68                       | 1091| 311 | 3167| 3979                      | 11                       | 53 | 28 |
| 2                | 12                       | 507                      | 1374| 738 | 1998| 5978                      | 23                       | 44 | 31 |
| 5                | 17                       | 176                      | 1332| 529 | 4608| 10586                     | 22                       | 42 | 30 |
| 3                | 20                       | 164                      | 636 | 313 | 1591| 12177                     | 24                       | 40 | 33 |
| 4                | 24                       | 0                        | 225 | 74  | 648 | 12825                     | 15                       | 38 | 22 |

Figure 9: Sediment concentration and load variation during study

5. Conclusion
The Pelton turbine was coloured and images throughout the monsoon season were obtained. Analysis of these images helped in classifying Pelton buckets into various erosion zones. Thicker coating in these areas will retain the profile of the surface for a longer period of time which will reduce the efficiency drop due to erosion. In this study, manual samples have been collected at the plant throughout the study period and an acoustic instrument for continuous sediment monitoring was used for a shorter period of time. These values were used for sediment load calculation. The main conclusions from this study are given below.

1. Paint method is useful in finding the initiation of erosion and erosion proneness in Pelton bucket
2. The Pelton bucket is most prone to erosion in middle portion of zone 2 and zone 3 from inside and outside of Pelton bucket respectively.
3. The gradual removal of material from Pelton bucket due to erosion can be monitored with images throughout the monsoon/rainy season.

4. The sediment properties like concentration and size, which are vital for erosion study, vary significantly during the monsoon/rainy season. It is recommended to measure them with continuous monitoring instruments to capture the high sediment load events.

5. Bypassing/Skipping the high sediment load events will save the turbine from erosion; however, a detailed financial analysis is required for the same.

The information from this study is useful to turbine designers/manufacturers and hydropower plant managers in deciding the coating surfaces in case of erosion and designing/testing erosion friendly turbine buckets. More studies related to erosion in hydro turbine are required to visualize and quantify erosion.

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