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Financial analysis for optimization of hydropower plants regarding hydro-abrasive erosion: A study from Indian Himalayas

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Abstract. The hydro-abrasive erosion poses challenges for smooth and efficient operation of existing as well as new hydropower plants (HPP). The loss in revenue is caused due to reduced generation on account of reduced efficiency, erosion of plant machinery, down time for repair and maintenance as well as additional expenditure on restoring the machinery and efficiency. In this study, simultaneous measurement of suspended sediment properties (particle size, concentration, shape and mineral content), hydro-abrasive erosion and reduction in efficiency was carried out in a HPP located in Indian Himalayas. The measured values were used, with available models, to calculate gradual loss of efficiency of the turbine and other losses due to repairs, replacements and shutdowns caused by hydro-abrasive erosion. In the financial analysis, costs involved in preventive measures such as coating was included to find out an optimum strategy regarding hydro-abrasive erosion. The losses in operating the uncoated turbine were found about 16% whereas the cost of coating was calculated as 11% of the uncoated turbine cost at the study HPP. The gradual efficiency loss, a major loss, increased rapidly with operation time and amounted to 37% of the total loss. A criterion for decision making was also developed.

1. Introduction

In geologically young mountains like the Andes and the Himalaya, high sediment content during high flow season causes hydro-abrasive erosion of the turbine and other components coming in contact with the flow [1-4]. It leads to gradual reduction in efficiency of the turbine due to a change in profile of the turbine blades and other components such as guide vanes, nozzle rings, nozzles etc. severely affected by erosion. The loss in revenue is caused due to reduced generation on account of reduced efficiency, erosion of plant machinery, down time for repair and maintenance as well as additional expenditure on restoring the machinery and efficiency. Researchers attempted to quantify the loss of efficiency due to erosion [5-7]; however, verification and broad acceptance of the developed models still remain in progress as the models were developed for specific laboratory or field conditions.

The output of a HPP gradually decreases as erosion of the turbine increases. Pradhan et al. [8] performed thermodynamic efficiency tests of a Francis turbine in Jhimruk HPP (3×4 MW) at an interval of 11 weeks and found 4% reduction in efficiency at the best efficiency point (BEP). The leakage at labyrinth seals and erosion in guide vanes contributed 50% and 25% of the reduction in efficiency respectively. Bajracharya et al. [5] analysed the erosion of a Pelton turbine and suspended sediment characteristics of Chilime HPP (2×11 MW) to predict a loss of 1.21% of turbine efficiency during the initial year of operation. The loss in efficiency was projected at 4% for the consecutive year if the same
turbine would have continued to produce electricity without any repair/restoration to the original profile. In an extensive erosion study, Felix [1] and Abgottspen et al. [9] measured the change in Pelton turbine efficiency caused by erosion and restoration of bucket profiles with grinding work at Fieschertal HPP (2×32 MW) from the year 2012 to 2016. Due to a major sediment event of 20 g/l SSC in 2012, the splitter height was found to reduce by 3 to 5 mm [1].

The eroded turbine is repaired by welding with suitable electrodes and ground to obtain the initial profile of blades or buckets. Further, the repaired runner goes through the process of heat treatment to relieve stresses during welding and grinding processes. Repair of eroded turbines is a labor-intensive work; hence cost of maintenance varies in different parts of the world depending upon wages [10]. In the Himalayan region, the hydropower companies usually prefer to repair the turbine rather than to replace them because of low labour cost which is in the range of 10% to 15% of the replacement cost. The challenge for the repair of eroded turbines is to select and use the proper welding and coating material to get the best performance from the turbine. Regular inspections are recommended to find out the repair cycle [10-11]. Delaying the repair may increase the risk of unplanned outage, increased overhaul cost and even make components irreparable due to excessive damage.

The decision of refurbishment, maintenance and replacement is also challenging for engineers and plant operators working on hydropower plants operating on erosive conditions. Thapa [10] discussed the economic aspects of hydropower plants due to erosion but also mentioned that a long term approach is needed to find the optimal operating regime of a power plant. The operation and maintenance cost for hydropower plants increases over the period of time and the rate of increment is high in case of erosion. The restoration of the output can be achieved with rehabilitation to initial rated output and can even be increased by redesign in some cases [12-13]. Hard coatings are applied as a preventive measure to reduce the gradual decrease in the output of hydropower plants due to erosion. When a coating is applied on turbine surfaces, a minor amount of efficiency is lost due to higher roughness of coated surfaces; however, the gradual reduction of uncoated turbine efficiency due to erosion is faster than that of coated turbines over the period of operation [12-13].

2. Site description
The study HPP, 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. In Unit-1, the Pelton turbine had uncoated buckets whereas Unit-2 had coated buckets. The combined desilting tank and forebay of the plant are designed to remove sediments particle size greater than 200 μm detailed in [3].

3. Methodology
Simultaneous measurements of suspended sediment, hydro-abrasive erosion and efficiency reduction were performed in study plant [2-4]. The obtained values were used to calculate the financial losses due to hydro-abrasive erosion are as follows:

1. Gradual efficiency drop loss - Reduction in electricity production due to reduced turbine efficiency
2. Downtime loss - No electricity production during shutdowns on account of dismantling, replacements and reinstallations
3. Repair loss - Repair cost to restore the turbine, especially welding and grinding
4. Heat treatment, balancing and transportation loss - Cost of heat treatment and balancing including cost of transportation, as required
5. Replacement loss – Cost of new runner and other components in case of replacement
6. Non-compliance loss - Penalty on account of non-compliance with generation plan

In addition to these components, the optimization consideration with respect to erosion requires the calculation of preventive measures like coating of turbines and their components [13-14].
3.1 Calculation of gradual efficiency drop loss

The losses in electricity generation due to gradual decrease in efficiency were assessed with four efficiency reduction models and measuring the efficiency of the Unit-1 in the study plant – (a) before the start of the operation on 5th May 2015 and (b) before a major overhaul and replacement of eroded components on 24th July 2015. The efficiency measured during the time period was used to calibrate efficiency loss models of Bajracharya et al. [5], Takgi et al. [15] along with two efficiency drop models considering efficiency reduction in proportion to particle load (PL) [11] and suspended sediment load (SSL). These plant specific calibrated models were used for obtaining the gradual loss of efficiency and electricity in the study HPP.

3.1.1 Bajracharya et al. [5] efficiency reduction model

A plant specific calibration factor \( K_{Bajra} \) is introduced in the model of Bajracharya et al. [5] to bring it in the form of eqn. (1).

\[
\eta_{loss, Bajra} = K_{Bajra} \cdot 0.1522 \cdot (dS/dt)^{0.6946}
\]  

(1)

where,

\( \eta_{loss, Bajra} \) = efficiency reduction calculated from Bajracharya et al. [5] efficiency reduction model,

\( K_{Bajra} \) = calibration factor for Bajracharya et al. [5] efficiency reduction model,

\( dS/dt \) = erosion rate, mm/year.

The erosion rate mentioned in eqn. (1) is calculated using IEC 62364 [11]. The efficiency reduction from this equation is non-linear and incorporates all factors involved in IEC 62364 [11].

3.1.2 Takgi et al. [15] efficiency reduction model

The relation of linear decrease in efficiency due to erosion, from Takgi et al. [15], is modified for field application in the form of eqn. (2) with the introduction of the plant specific calibration factor \( K_{Takgi} \).

\[
\eta_{loss, Takgi} = K_{Takgi} \cdot C_w
\]  

(2)

where,

\( \eta_{loss, Takgi} \) = reduction in turbine efficiency with sediment-laden flow calculated from the modified Takgi et al. [15] efficiency reduction model,

\( K_{Takgi} \) = plant specific calibration factor for the modified Takgi et al. [15] efficiency reduction model,

\( C_w \) = fraction of solid by weight.

The value of the plant specific calibration factor was obtained as 0.085 from erosion studies in a Francis turbine test rig [15]; however, the factor was obtained specifically to the study plant here. The fraction of solid by weight i.e., SSC mentioned in eqn. (2) was measured using various suspended sediment measurement methods [3]. The efficiency reduction from this equation is linear and incorporates only SSC.

3.1.3 PL efficiency reduction model

The parameter particle load (PL) is introduced by IEC 62364 [11] to combine different suspended sediment parameters like concentration, size, shape and hardness contributing to erosion. The efficiency reduction is assumed proportional to the particle load passed through the turbine and is calculated using eqn. (3).

\[
\eta_{loss, PL} = K_{PL} \cdot PL
\]  

(3)

where,

\( \eta_{loss, PL} \) = reduction in turbine efficiency proportional to PL from IEC 62364 [11],
\( K_{PL} \) = plant specific calibration factor for efficiency reduction proportional to \( PL \), and
\( PL \) = particle load as defined in IEC 62364 [11].

The \( PL \) for the Toss HPP is calculated using measured values of suspended sediment parameters.

### 3.1.4 SSL efficiency reduction model

The suspended sediment load (SSL) passed through a turbine is commonly used in literature as a measure to erosion [12, 16-17]. The efficiency reduction is assumed proportional to the SSL passed through the turbine and is calculated using eqn. (4).

\[
\eta_{\text{loss, SSL}} = K_{SSL} \cdot \text{SSL}
\]  

(4)

where,
\( \eta_{\text{loss, SSL}} \) = reduction in turbine efficiency proportional to SSL,
\( K_{SSL} \) = plant specific calibration factor for efficiency reduction proportional to SSL, and
\( \text{SSL} \) = suspended sediment load.

The methodology to calculate SSL of the study plant is detailed in Rai and Kumar [3]. The model considering efficiency reduction proportional to SSL considers the flow and duration in addition to the SSC values, the lone parameter considered in modified Takgi et al. [15] efficiency reduction model.

### 3.2 Calculation of downtime loss

Downtime of the plant machinery may be due to several reasons like fault in power evacuation, scheduled outage, forced outage due to failure of a component and operational measures like stopping the plant at limiting value of SSC in inflows. In the financial analysis, only the downtime due to erosion problems has been considered and is calculated using eqn. (5).

\[
E_{\text{down}} = t_{\text{down}} \times C_{\text{unit}} \times W_{\text{available}}
\]  

(5)

where,
\( E_{\text{down}} \) = electricity generation loss due to downtime, kWh
\( t_{\text{down}} \) = duration of downtime, hour
\( C_{\text{unit}} \) = rated generating capacity of unit, kW, and
\( W_{\text{available}} \) = water availability factor during the duration of downtime.

The water availability factor varies from the minimum value 0 to the maximum value 1. During lean season when the available water can be entirely used for generation using other operating units and no surplus water is wasted, the water availability factor is 0. This is the ideal time for repair and maintenance as it amounts to no loss of electricity generation. During rainy season, this factor has the maximum value which leads to the maximum loss for downtime.

### 3.3 Calculation of repair loss

The repair of eroded turbines consists of mainly two processes (a) welding and (b) grinding. During the welding process, material is deposited on the turbine bucket/blade surfaces to fill the material removed by erosion. The grinding process is applied to restore the original profile with the deposited weld material. For obtaining the rate of various repairs, the turbine manufacturers in India were contacted. After welding a heat treatment is needed, which usually cannot be done on site.

#### 3.3.1 Methodology for calculating welding cost

The cost of welding depends on the amount of material removed due to erosion and the site specific factor. With increased erosion duration, the amount of material removed and the cost of welding increase. Hence, the cost of welding depends on the instances of repair. The IEC 62364 [11] model was used to calculate the amount of erosion for different operation durations such as May, June and July 2015. For the entire study period, the obtained amount of erosion from the model is verified with the measured value of
erosion. The amount of erosion along with the rate of welding in term of metal quantity obtained from the manufacturers is used to obtain the cost of welding for all above durations.

3.3.2 Methodology for calculating grinding cost
The cost of grinding depends on the surface area of the turbine and its components. The surface area of the turbine parts to be ground generally remains constant even when the entire surface encounters erosion. Hence, the cost of grinding remains constant and does not depend on the instances of repair. The surface area of one uncoated bucket was obtained from the 3D-scanned image. The rate of grinding costs with respect to the surface area was obtained from the turbine manufacturers.

3.4 Calculation of heat treatment, balancing and transportation losses
The costs involved remains constant for (a) heat treatment and balancing of the entire runner and (b) for transportation of the turbine from the hydropower plant to the runner balancing site. This cost depends on the location of the hydropower plant and its accessibility; but, it does not depend on the instance of repairs. The heat treatment, balancing and transportation costs of the study plant were obtained from the history of the plant.

3.5 Calculation of replacement loss
The turbine runner is preferred to be repaired in Himalayan region because of lesser labour cost [10]; however, other components such as nozzle, nozzle rings, guide vanes, labyrinth rings etc. are replaced with new ones. In excessive damage of turbines, the old eroded runner also requires to be discarded and replaced by the new runner. The welding material has lesser strength against erosion [18] than the original steel and repeated welding on the runner surface may give rise to brittleness and fracture. Hence, repaired turbines are generally discarded after 3 to 4 repairs [10]. For the study plant, the cost of various components and its replacement frequency was obtained from the history of the plant.

3.6 Calculation of non-compliance loss
There may be a penalty for non-compliance with the generation plan i.e., disability to generate electricity as projected by the regulating agency due to erosion or failure of a component. The practice of shutting down a plant above a limiting value of SSC for avoiding erosion may also induce non-compliance losses.

3.7 Calculation of preventive measures cost
In view of availability of 3 months data, the coating option has been explored as a preventive measure in the study plant. Generally, hard coating, using high velocity oxy fuel (HVOF) process, is applied on the turbine surface [14]. The cost of per unit area for coating is obtained from turbine manufacturers and is used with the surface area calculated from 3D-scanned images of Toss HPP buckets to obtain the cost of coating the turbine.

4. Results and discussions
For the study plant, the results of financial analysis are presented here for each cost component.

4.1 Efficiency of the turbine unit
For the turbine unit with uncoated buckets, the relative efficiency scaled with highest efficiency before erosion is shown in figure 1. The uneroded turbine in figure 1 refers to the turbine installed in the unit on 5th May 2015 and the eroded turbine refers to the turbine eroded till 24th July 2015. The efficiency drop of the unit was in the order of 6% at the range of 60% to 80% load and the efficiency drop increased rapidly for higher loads.
The drop of efficiency from measured values was calculated as per linear interpolation to obtain efficiency values at different operating loads as presented in Table 1.

<table>
<thead>
<tr>
<th>Operating load (%)</th>
<th>Efficiency drop of the uncoated unit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>5.86</td>
</tr>
<tr>
<td>70</td>
<td>6.14</td>
</tr>
<tr>
<td>80</td>
<td>7.43</td>
</tr>
<tr>
<td>85</td>
<td>10.75</td>
</tr>
<tr>
<td>90</td>
<td>16.40</td>
</tr>
</tbody>
</table>

Due to excessive leakage of water, vibration and safety concerns, the efficiency testing was limited to maximum load of 91\% at 4 nozzle opening for the eroded turbine. Similar drop in efficiency of 4\% of the turbine unit in Jhimruk HPP was observed between 1st September and 11th November 2003 [8].

4.2 Loss due to gradual efficiency reduction
The gradual loss of efficiency during the measurement period, obtained from four different models, is presented in figure 2. The rate of efficiency loss due to erosion was initially less and increased to the maximum at the final part of the study as shown with gradients of straight lines in figure 2. This variation was caused by the higher SSC values in the inflows.

![Figure 1. Efficiency reduction due to hydro-abrasive erosion in Toss HPP.](image)

![Figure 2. Gradual efficiency loss calculated from 4 models.](image)
The loss of electricity generation due to this gradual reduction in efficiency of the turbine unit was calculated assuming the plant to be operational at full load during the 12 week study duration. The loss of energy units (kWh) was calculated as per four models chosen for gradual efficiency reduction calculation and is shown in figure 3.

![Figure 3. Energy loss due to gradual decrease in efficiency calculated from 4 models.](image)

The shut-downs of the plant due to power line maintenance or some forced reasons were taken into account. The valleys in figure 3 were formed due to the intermediate shutdowns due to reasons other than erosion. As these shut-downs were not caused by erosion, these were excluded in financial analysis of erosion in the plant. The electricity generation lost due to gradual efficiency decrease is given in Table 2.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Model applied</th>
<th>Calibration factor, K</th>
<th>Electricity generation loss (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bajracharya et al. [5] model</td>
<td>36,945.700</td>
<td>107,500</td>
</tr>
<tr>
<td>2</td>
<td>Modified Takgi et al. [15] model</td>
<td>0.126</td>
<td>135,000</td>
</tr>
<tr>
<td>3</td>
<td>Particle load model from IEC 62364 [11]</td>
<td>5.659</td>
<td>152,500</td>
</tr>
<tr>
<td>4</td>
<td>Suspended sediment load model</td>
<td>0.001</td>
<td>150,500</td>
</tr>
</tbody>
</table>

4.3 Loss due to downtime

The operators of the study plant maintained the inventories of spares for each component susceptible to erosion especially spear head, nozzle ring, nozzle shield and turbine runner available for replacement from their past experience. The spares available for replacement reduced the downtime effectively. Moreover, all the components except the runner were replaced since replacement was relatively more economical than the repair. The spear head and nozzle ring were eroded in axial direction with thin eroded lines along its surfaces similar to erosion patterns reported in literature [5, 19].

The time required for changing various turbine components, their major issues and frequency of change for the study plant is obtained from plant experience and is provided in Table 3. As per values from the Table 3, the total downtime for the major overhaul at the end of 23rd July 2015 was 12 hours. The turbine runner was not changed during that period; however, two nozzle rings and one nozzle spear head were replaced. Assuming the turbine to be operated at rated power, the loss of electricity from Unit-1 during downtime was 60,000 kWh as per eqn. (5) because water was available during whole high flow period from April to September each year since commissioning of the plant in 2008.
Table 3. Time to change various eroded components of runner at Toss HPP.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Turbine part</th>
<th>Major issues</th>
<th>Time required</th>
<th>Detection criteria</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Runner</td>
<td>Highly eroded after each high flow season</td>
<td>24 hours</td>
<td>Visual inspection</td>
<td>Changed every year</td>
</tr>
<tr>
<td>2</td>
<td>Nozzle ring</td>
<td>No pressure building, sediment erosion</td>
<td>5 hours</td>
<td>Visual inspection and working condition</td>
<td>Frequent change once or twice/year</td>
</tr>
<tr>
<td>3</td>
<td>Nozzle spear head</td>
<td>breakage of internal thread and minor erosion</td>
<td>2 hour</td>
<td>Visual inspection and working condition</td>
<td>Change once per year</td>
</tr>
<tr>
<td>4</td>
<td>Nozzle shield</td>
<td>Excessive vibrations</td>
<td>2 hours</td>
<td>Visual inspection</td>
<td>Changed once in 4 years</td>
</tr>
</tbody>
</table>

4.4 Losses due to repairs, replacements and obligations

It is necessary to monitor the extent of erosion in turbine components at regular intervals (dependent on the site condition and past experiences) to limit the erosion to such an extent that the repair of the eroded part is feasible.

4.4.1 Repair cost

Generally, the repair cost of small turbines less than 25 MW capacity depends on labour charges comprising of number of man hours of work and wage rate of person engaged for such work. Sinha [20] reported that the welding cost (including labour cost) was INR 1,000 per kg of turbine material and grinding cost (including labour cost) was INR 40,000 per m² in 2010 for repairing a small turbine.

In the study plant, the loss of weight of the turbine after December 2015 was 75 kg, which is 5% of the total runner weight, measured before transporting the turbine to the workshop for repairs. The turbine in the study plant was not repaired on 24th July 2015; but, the material removed was calculated based on suspended sediments passed through turbine using erosion models. IEC 62364 erosion model [11] was used with repair rates to obtain repair cost for various durations such as May, June and July for the study plant. The heat treatment, balancing and transportation costs were also not needed for these 3 months duration.

4.4.2 Replacements and obligation costs

The eroded components need to be repaired and brought back to their original profile before being reinstalled. For all eroded components except the turbine runner, it was cost effective to use a new one rather than repairing the eroded one because of comparatively lesser cost of the new components for Toss HPP. The cost of various components affected by erosion in the study plant is obtained from plant history and is provided in Table 4. Here, one nozzle spear head and two nozzle rings were replaced amounting to INR 0.35 million.

Table 4: Cost of turbine components susceptible to erosion in Toss HPP.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Component</th>
<th>Cost (INR Million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>New Turbine</td>
<td>9.000</td>
</tr>
<tr>
<td>2</td>
<td>Nozzle spear head</td>
<td>0.200</td>
</tr>
<tr>
<td>3</td>
<td>Nozzle ring</td>
<td>0.075</td>
</tr>
<tr>
<td>4</td>
<td>Nozzle shield</td>
<td>0.025</td>
</tr>
</tbody>
</table>

100 Indian National Rupee (INR) = 1.560 USD

For various hydropower plants around the world, the penalty for not generating the committed electricity would add to the losses due to hydro-abrasive erosion. For the study plant, being small hydro there was no penalty for electricity generation; hence, there was no loss due to obligations in this case.
4.5 Preventive measures and strategy for optimal plant operation

The preventive measure with respect to the turbine such as coatings and CFD analysis are discussed here. Further, the optimization considerations with respect to various losses and decision making strategy are presented for the study plant to observe the consequences of repair at the end of months May, June and July.

4.5.1 Cost of coating

Coating of turbine components is a very effective option to reduce the damaging effect of erosion. This technology is particularly well suited to runners with easy blade access, enabling coating material to be sprayed onto all surface areas manually or using a robot. The high abrasion and fatigue resistance of the HVOF coating is achieved using tungsten carbide ceramic powder embedded in a metal substance. The application technique used creates a high-density layer of coating with very strong bonding capabilities, which is on an average 0.3 mm thick. The spray gun is required to be maintained at an angle of 90 degree with a ±15 degree.

Cost of HVOF coating = INR 0.2 Million per m² for a thickness of 0.3 mm [20].

In case of the study plant, the total surface area of buckets of a Pelton runner is calculated as 6.62 m². Hence, the cost of coating will be about INR 1 million assuming 75% of the bucket surface requires coating.

4.5.2 Strategy for optimal operation of plant

The cost of coating, calculated from the rates obtained from the above mentioned method was about 11% of the cost of the new uncoated turbine. The loss due to gradual efficiency reduction calculated from PL model and other three models are provided in Table 5. The losses due to various components at the end of months May, June and July are provided in Table 6. The losses were around 15%, 18% and 23% of the cost of the uncoated turbine when repaired at the end of May, June and July 2015 respectively considering cost of repair, heat treatment, balancing and transportation each time. Hence, the loss of revenue in repairing the uncoated turbine was higher than the coating of new uncoated turbine in the study plant. Moreover, this cost estimation is only due to erosion of initial 3 months of installation with around 1400 hrs of operation. As the coating cost is only 11% of the new uncoated runner, it is profitable to apply the coating on new runner as it reduces the efficiency loss and allows the turbine to operate for longer duration.

Table 5. Losses due to gradual efficiency reduction calculated from models.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>13,000</td>
<td>24,000</td>
<td>53,000</td>
<td>45,000</td>
</tr>
<tr>
<td>June</td>
<td>145,000</td>
<td>238,000</td>
<td>285,000</td>
<td>284,000</td>
</tr>
<tr>
<td>July</td>
<td>378,000</td>
<td>414,000</td>
<td>424,000</td>
<td>424,000</td>
</tr>
</tbody>
</table>

Table 6. Losses involved for repair schedule at the end of May, June and July 2015 (in INR).

<table>
<thead>
<tr>
<th>End of month</th>
<th>Gradual efficiency drop loss using PL model</th>
<th>Downtime cost</th>
<th>Repair cost</th>
<th>Heat treatment balancing, and transport cost</th>
<th>Replacement cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gradual efficiency drop loss using PL model</td>
<td>Downtime cost</td>
<td>Grinding cost</td>
<td>Welding cost</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>53,000</td>
<td>300,000</td>
<td>265,000</td>
<td>6,000</td>
<td>50,000</td>
</tr>
<tr>
<td>June</td>
<td>285,000</td>
<td>300,000</td>
<td>265,000</td>
<td>17,000</td>
<td>50,000</td>
</tr>
<tr>
<td>July</td>
<td>424,000</td>
<td>300,000</td>
<td>265,000</td>
<td>19,000</td>
<td>50,000</td>
</tr>
</tbody>
</table>
For decision making in case of erosion conditions, researchers derived cut-off limit of SSC value for plant operation [7, 21-22]. For financial analysis and decision making in case of erosion conditions in a hydropower plant, erosion models were used in this research work. Various losses were plotted as shown in figure 4 with the help of these erosion models. The loss components for all the months are shown in figure 4 and it allows a better timing for deciding the repair and maintenance for an erosion affected hydropower plant. For the study plant, the loss component due to gradual reduction of efficiency increases rapidly with each passing month. The plants may fix a limiting value on this loss as the criteria for overhaul or replacing the turbine.

![Figure 4. Various losses and their variations with time in the study plant.](image)

5. Conclusions
In this paper, various losses due to erosion in a hydropower plant have been discussed. The costs involved in preventive measures such as coating the turbine blades were also discussed. The models available for calculating gradual loss of efficiency of turbine were applied for calculating loss of efficiency in the study plant Toss HPP. As the erosion data required for financial analysis was not available for the whole high flow period (April to September), the analysis has been carried out for 3 months duration only. The losses in operating the uncoated turbine for the duration has been found as 15.7% whereas the cost of coating was 11% of the uncoated turbine cost. Thus, the option of the coated turbine has been found more economical for Toss HPP. The gradual efficiency loss was a major portion of the total loss. Furthermore, the cost of preventive measures and a criterion for decision making has been presented. For decision making, the losses for repairing the turbine at the end of three months May, June and July has been assessed. To assess the complete loss due to erosion and optimum measures to minimize the losses, long term data needs to be obtained at a hydropower plant.

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