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Review on erosion phenomenon, maintenance, and financial calculation of lifetime as an asset for Pelton turbines

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Abstract. Prevention of greenhouse emissions is the top priority for all countries, which urges them to switch to renewable energy as much as possible. Hydropower is one of the renewables that have high flexibility and at the same time compatibility to be used with any other renewable sources. Moreover, hydropower plants operating in the Himalayas, Andes, and Alps are facing operational challenges due to the high concentration of sediment loads in rivers. Although the arrangement of traditional sediment control mechanisms like dams and sand traps, the erosion tendency of hydro-turbine components operating in this sediment-laden water increases with the increased concentration of sediments. Much past research has been directed towards understanding sediment behaviors, investigation of flow, and effect of concentration, shape, and size, especially with Francis turbines. However, there are very fewer studies regarding sediment erosion and flow behavior in the case of the Pelton turbine. Hence, delving deeper into the flow characteristics, sediment behavior, and performance of the Pelton turbine is important to better understand the flow and sediment pattern of these types of turbines. The paper consists of the evaluation of studies conducted on the flow pattern in the Pelton turbine buckets and its validation with the numerical analysis models using image processing. It is being used in the Waterpower Laboratory at the Norwegian University of Science and Technology, NTNU. This paper also evaluates the scope of investigations about erosion by sediments in Pelton buckets using image analysis and state-of-the-art technology in the hydropower sector. In addition, a review is done about the predictability of erosion based on the measurements of the quantity of sediments that passes through the turbine. This research paper can build a background for quantifying sediment erosion in Pelton turbines with a certain degree of error, which can be utilized as a reference in future studies. The life cycle estimation of a turbine is also analyzed with the consideration of its location and financial return requirements together with the type of maintenance that it may have and the repair that is foreseen, in the case of a non-coated surface.

Keywords: Erosion, Flow behavior, Image analysis, Pelton turbine, Sediment particles.

1. Introduction

Hydroelectric power is one of the flexible renewable sources and is supposed to contribute the most to slowing down the pace of climate change [1]. Hydropower plants operating in sediment-laden water are facing severe operational challenges due to higher sediment loads resulting from irregular rainfall intensities caused by global warming. The erratic rainfall intensity increases the sediment loads by about 1.6% for every 1% change in rainfall although sediment-decreasing factors like agriculture and the construction of big dams are considered [2].

The feasible areas of the rivers for hydropower projects are shown in Figure 1 along with the rivers which are excessively used for irrigation, water consumption, fragmentation, and regulation. It can be seen that the feasibility of building a new hydropower project seems possible in rivers that originated from young mountain ranges such as the Andes and the Himalayas. These rivers are facing challenges of high sediment loads which are increasing each year due to changes in rain patterns and the melting of glaciers [3, 4]. The effects of such a higher concentration of sediment in this river have been reflected in the severe wear and tear of hydro turbines operating in these regions. This wear and tear increase the maintenance costs and decrease hydropower generation, which is increasing each year.

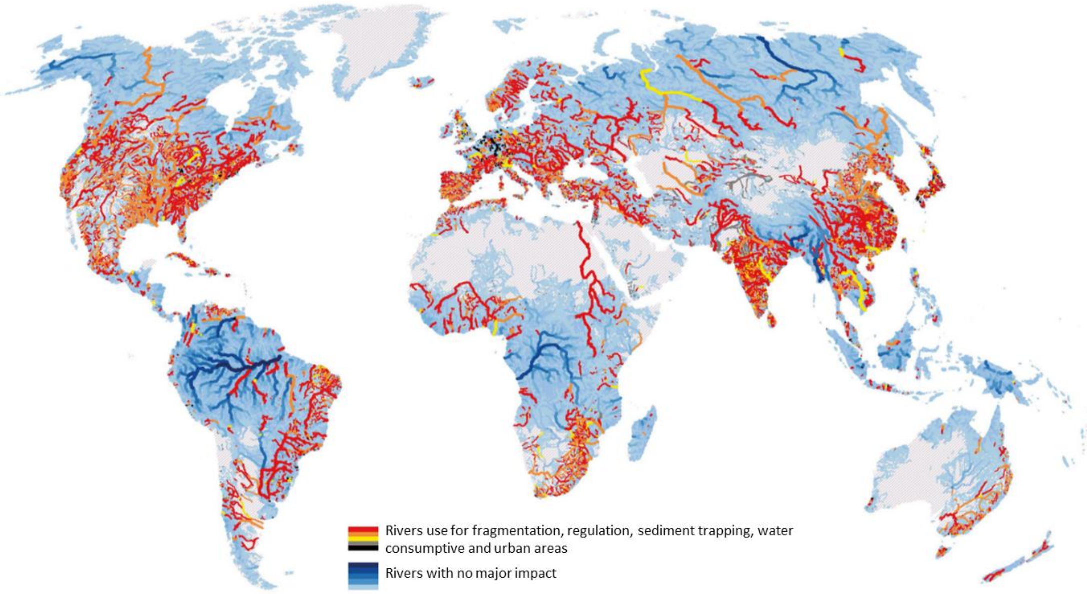

Figure 1. Map of rivers without alterations in their path (modified from Grill 2019).

Dams, and sand traps at the intakes and inside the tunnels, are used for the retention of the sediments to reduce their passage through the turbines. The effectiveness of these infrastructures in controlling sediments is calculated with different methods and depends on various hydraulic and hydrological factors apart from the sediment properties [5].

Due to their impact on river biodiversity, nutrient transport, and spawning habitat disturbances, dams are facing increased regulation by environmental agencies [6, 7]. Currently, new dam designs are evaluated considering the management of sediment loads, minimizing their impact on the environment, and respecting the transit of fish, which are under ecological standards being implemented [8]. The capacity of dams around the world is decreasing by about 1% annually [8, 9]. All these considerations related to sediment handling directly impact the turbine. It is important to plan the overhauling of a turbine according to the sediment loads, peak power demand, availability of resources, and the severity of erosion on the components.

This paper briefly reviews the research on sediment erosion, repair, maintenance, and useful lifetime for a Pelton turbine. First, an overview of sediment management and facilities of the hydroelectric power plant during the transportation of the sediments is discussed with its close connection with erosion in the Pelton turbine. Further, the erosion and the field investigation of erosion are discussed. Moreover, aspects directly related to the turbine, especially the flow of water and sediment through the turbine, are also evaluated. The financial part of a hydroelectric project includes the turbine as an asset subject to return-on-investment evaluations. To consider the complete evaluation of the life of a turbine, the types of maintenance that are practiced and their implication in the useful life of the turbine are analyzed. Finally, the useful life of a Pelton turbine is discussed, along with the author's perspective.

2. Erosion on Pelton turbines

There are many studies on the mechanics of how sediment induces erosion on turbines [10, 11]. The erosion in Pelton turbines is a peculiar phenomenon that combines several factors [12]. The predictability of how long a Pelton turbine can be operated continuously without maintenance is still a topic in development. IEC 62364 [13] had made good advancements in studying erosion behavior and gave a guideline for the prediction of erosion. However, there are some conditions where erosion occurs on all the surfaces of wet components of the turbine exponentially [14]. Figure 2 shows the irregular behavior of the erosion at different wetted surfaces of the Pelton turbine.

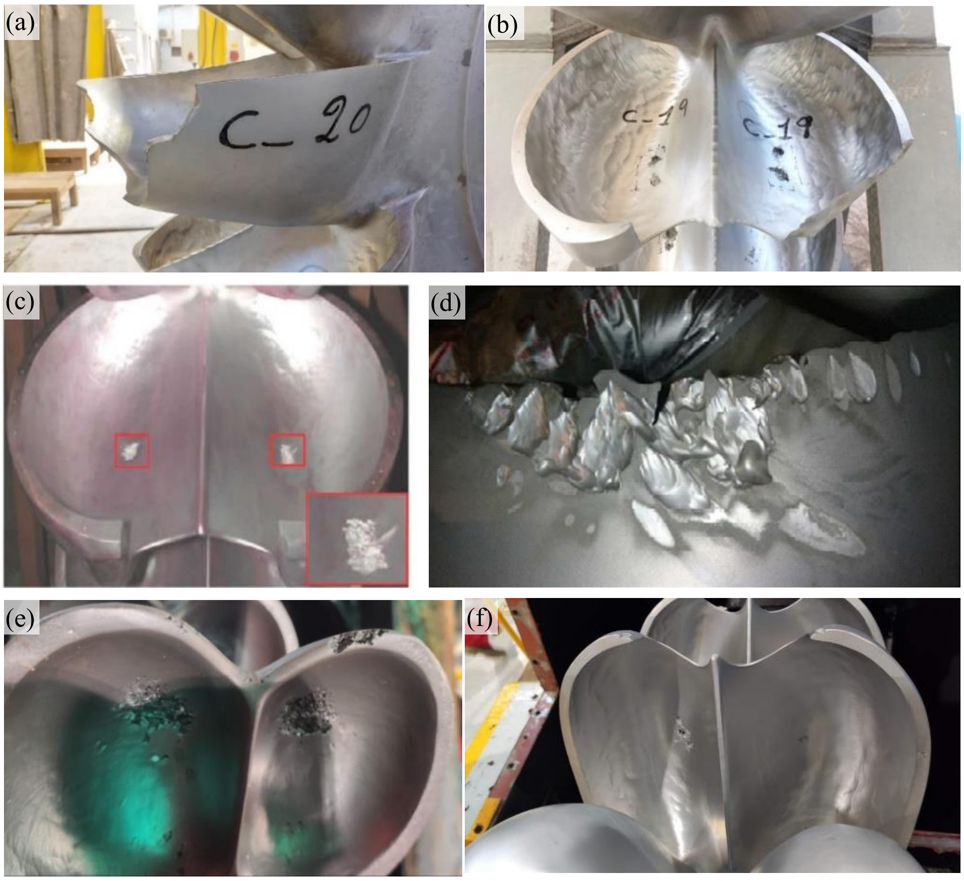

Figure 2. Cavitation on Pelton turbines. a & b) Cavitation on the inner surface of the bucket and break of a side of the outlet edge at Ancash-Peru. c) Cavitation on the inner surface, Smith [15]. d) Cavitation in the bucket splitter at Lima-Peru. e) Cavitation on the inner surface and lips of the bucket at Pasco-Peru. f) Cavitation on the inner surface of the bucket at Pasco-Peru.

When the erosion starts creating wave patterns on the surface it can be considered the beginning of cavitation [10] which can be observed in Figure 3. This type of pattern is also observed in the splitter where it loses material and will remain as a blunt-lateral surface for the jet of the water as the erosion advances [10].

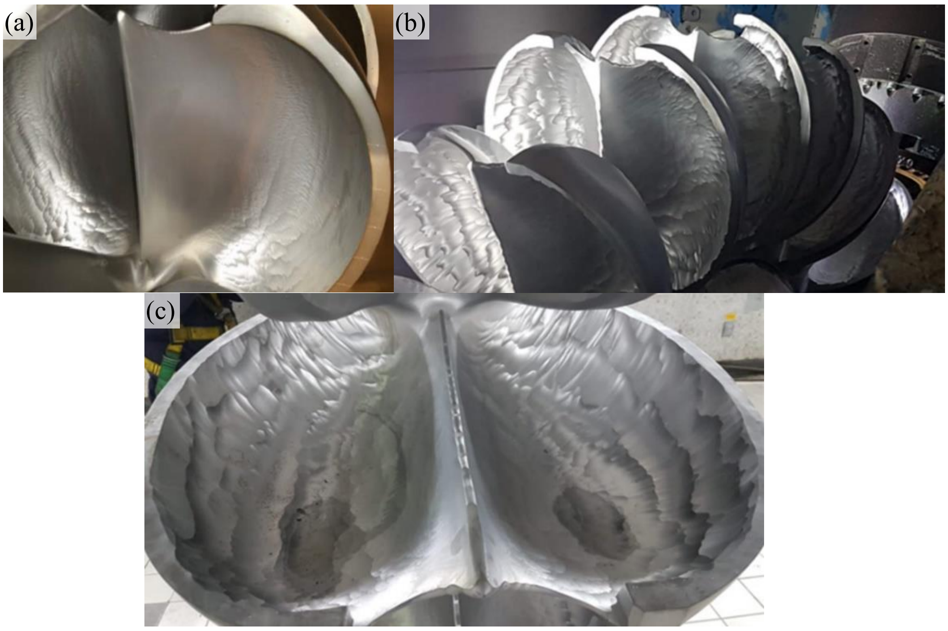

Figure 3. Regular erosion with starting of cavitation in Pelton turbine buckets. a) Runner after one year of operation at Pasco, Peru. b & c) Runner after four months of the rainy season at Ancash, Peru.

The combination of steady erosion and cavitation results in aggressive material loss, and irregularities in the wetted surfaces, and ultimately put the integrity of the Pelton runners at risk. These types of combinations can be seen in Figure 4 which can occur due to defects in the turbine, manufacturing as well as repairing process, and/or poor maintenance management.

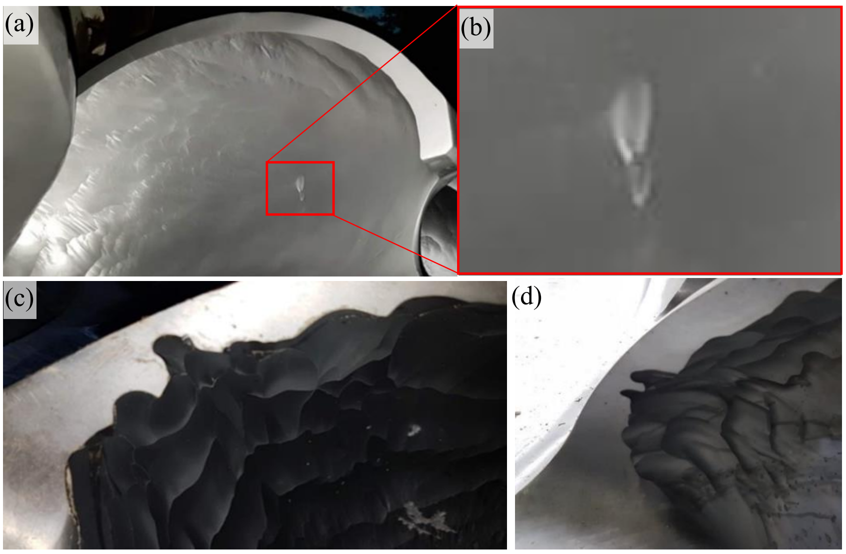

Figure 4. Aggressive erosion is caused by a combination of effects. a & b) welding reparation defect with erosion on the inner surface at Chiclayo Peru. c & d) Cavitation on the outlet edge at Ancash, Peru.

2.1. State-of-the-art research on Pelton turbine

One of the reasons Pelton turbines are selected for many hydropower projects in the overlap region is due to low vibration as compared to Francis turbines [16]. In addition, Pelton turbines have easiness of using the deflectors to prevent water hammer with sudden cuts in the water flow, and also facilitate maintenance inspections as it does not require the draining of the turbine chamber [18].

Since the first Pelton turbine came into operation in 1878 at the Mayflower Mine in Nevada City [19], its design and material have been improving and currently, almost 92% efficiency can be achieved on an industrial scale. In addition, it can work in a larger range with high efficiency and reduced cavitation damage compared to the Francis turbine [20]. The studies on the design and improvement of Pelton have been increasing in recent years due to independent academic work with industrial support [21, 22]. However, some complications make the research and development work of the Pelton turbine not at the same level as other hydraulic turbines. The flow regime that governs the water is classified by the dimensionless Reynolds number (Re), then after leaving the injector the water jet is governed by the Weber number (We) and finally, the interaction between the water and the rotating runner is handled under the regime of Froude number (Fr) [22].

The improvement in the efficiency of the flow of water inside the manifold has also been an area of research and numerical tools have been extensively used in recent years. Figure 5 shows that the design of the manifold is also important as bad design can account for an efficiency loss of 2-3% [23]. In addition, the efficiency drop can be increased up to a 2% increase in the nozzle due to the improvement in instability phenomena [24]. Although some interference might occur in the jets while working with 6 injectors and high specific speed [18], the deficiencies in the opening sequence of injectors have also been evaluated in ramp-up and ramp-down with their implications for vibrations and the need for hysteresis between operations to avoid repeated switching of the injector. But, there are also implications for the fatigue suffered by the turbine due to irregular loads [25]. Once the water leaves the injector, the losses in the jet can account for an overall decrease in turbine efficiency by 1.5% [26]. The losses in the jet are dependent on several factors, such as the distance between the injector and the bucket. For instance, the increase in the distance between the injector and the bucket more than four times the diameter of the jet generates a deformation of 1 mm in the axis of the jet [27].

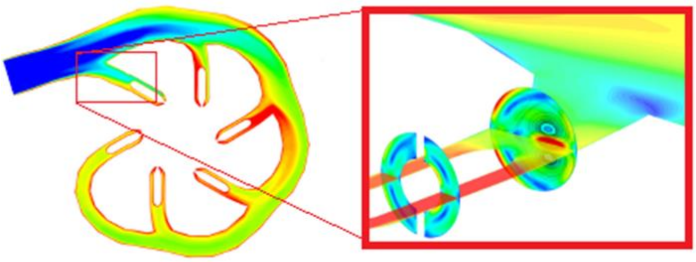

Figure 5. Inlet turbulence intensities in the Pelton manifold, modified from [23]

The use of tools like FEM and CFD during the design phase of the Pelton turbine enables to increase of the overall efficiency up to a significant level [28]. At the same time, the desire for higher efficiency demands the structures to be thinner forcing the limit of resistance to mechanical stress. High stress combined with the increasing starts and stops results in more turbine failures, and it has been increasing due to the popularity of hybridization of hydro energy to other renewable energy sources such as wind and solar energy. Stress loading due to repetitive cyclical loading can cause small cracks that are not easy to detect and over time can propagate suddenly leading to overall bucket failure [25].

Turbine casing has also been studied and efficiency improvements of 3% have been made in recent years with the use of modern research tools. The efficiency of the turbine also depends on the aerodynamics of the casing, deflectors, and injector covers [29]. However, major factors involved in the design of a turbine comprise the position of the jet, flow in the area of the lip, bend radius, and weight of the turbine [30]. The flow of the water jet over the Pelton bucket has been analyzed in several ways, initially in 2D with linear flow experiments [10] as shown in Figure 6, later with numerical simulations [31], and with the use of cameras in the adjacent bucket that evaluates the flow more closely [12, 32].

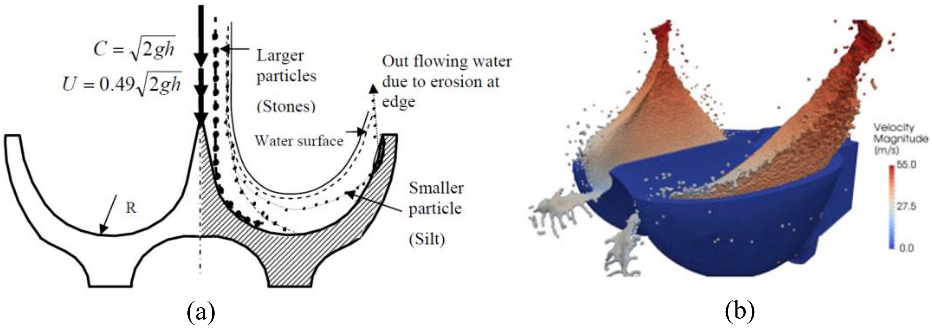

Figure 6. Representation of the sediment particles in the jet water over the buckets. a) 2D Representation of the path of sediments in the Pelton bucket [10]. b) 3D Computational modeling of the sediments in the Pelton bucket [33].

Electron microscopes have also been used to monitor the type of erosion presented in each part of the bucket [14, 34], which shows the action of the centripetal, Coriolis, and curved trajectory forces on the sediment particles [35].

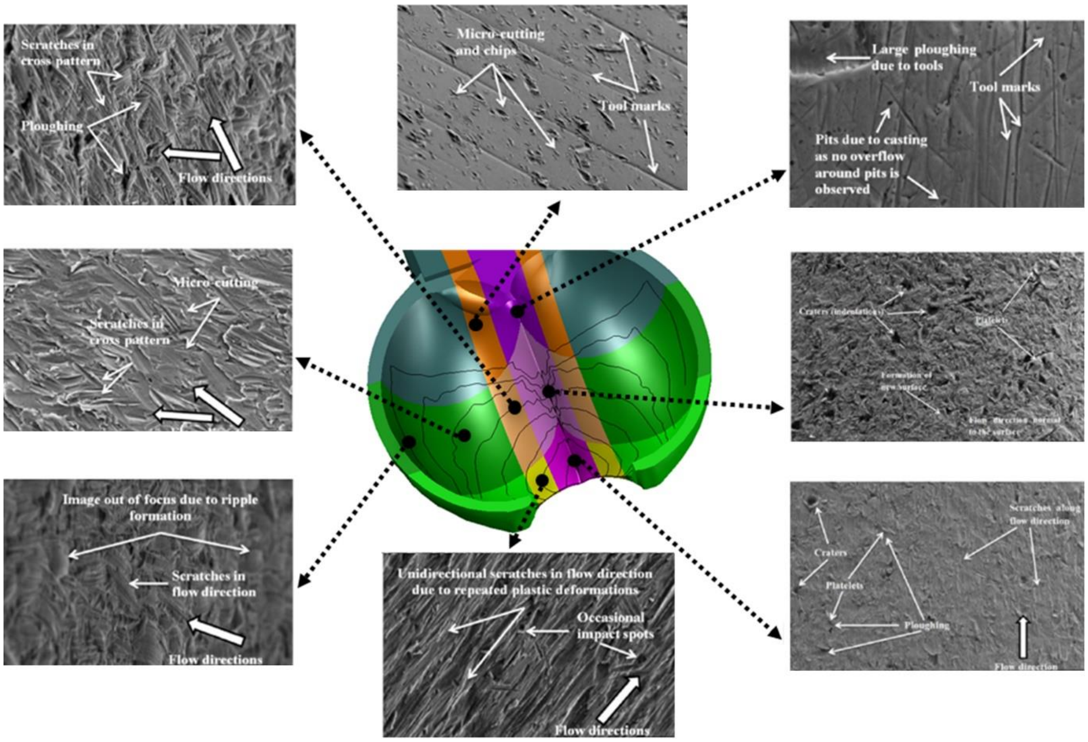

Figure 7. Representation of the evaluation of the behavior of the flow in black lines over the bucket and the images from the electron microscope [35, 36].

Many studies have been carried out in the areas of the turbine which are most susceptible to erosion, with the help of experimental, numerical [37], and simulation tools [33]. For instance, the study of wear zones and the type of sediment that affects those zones was carried out to show different erosion patterns in different areas of the bucket which can be observed in Figure 7. The patterns that an eroded Pelton turbine can have the combined effects of erosion, cavitation, and corrosion. However, it can have an individual impact in some areas. The wave patterns depend on the turbine material's hardness, the runner's speed, and sediment sizes, which are the main factors in the formation of undulations [10].

2.2. Measurement of erosion on Pelton turbines

The erosion measurement on the Pelton turbine is still carried out offline when the turbine unit is in the complete stop stage. Different tools have been used for the measurement of changes in the surface of the bucket. Some of the common tools are templates from the manufacturers, rulers, calipers, feeler gauges, electronic thickness measurement tools, and/or 3D scanners which are dependent on the erosion depth and the resolution to be achieved. The measurement of the changes in the thickness and profile of the Pelton bucket is shown in Figure 8 [38, 39]. The locations and minimum number of measurement points should be as per IEC 62364.

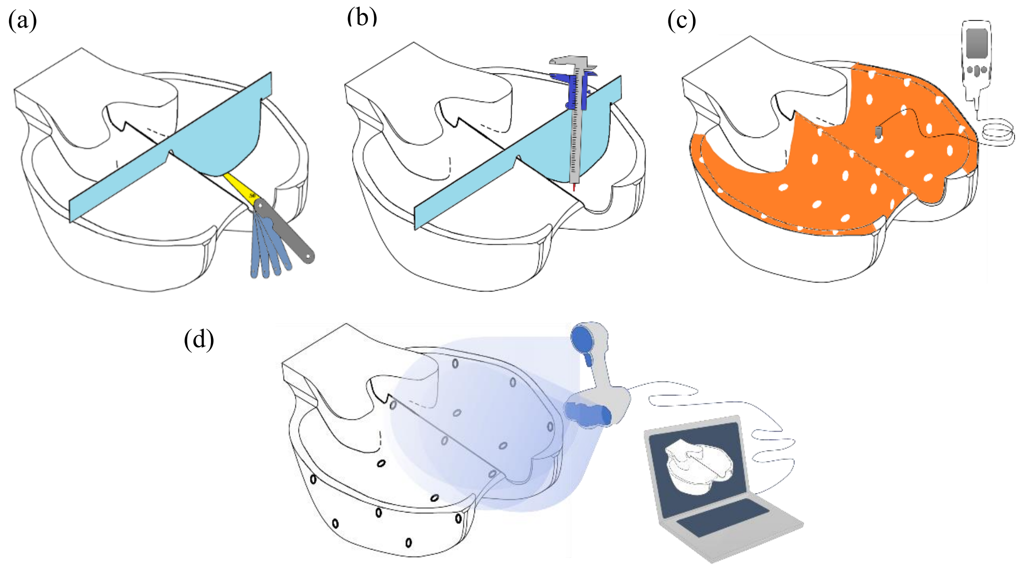

Figure 8. Graphic representation of most common measurement methods of erosion on the bucket of the Pelton turbine. a) Templates and feeler gauges. b) Templates and calipers. c) Electronic thickness measurement tools. d) 3D scanning.

Another powerful tool for the measurement and detection of cavitation, vortex, and bubbles in hydraulic machinery is image processing. With image processing, it is possible to investigate the evolution of cavitation and its effects on the blades [40, 41]. The use of image processing techniques has also been applied to measure erosion in turbines [42, 43]. MATLAB is a tool widely used for processing images and finding the ratio of the pixels and the eroded areas which are closest to the bucket tip and splitter as shown in Figure 9. The use of machine learning has also been growing now and then for processing images related to erosion to classify them [15]. Moreover, it has also been extensively in use to estimate the degree of erosion on flat surfaces [44].

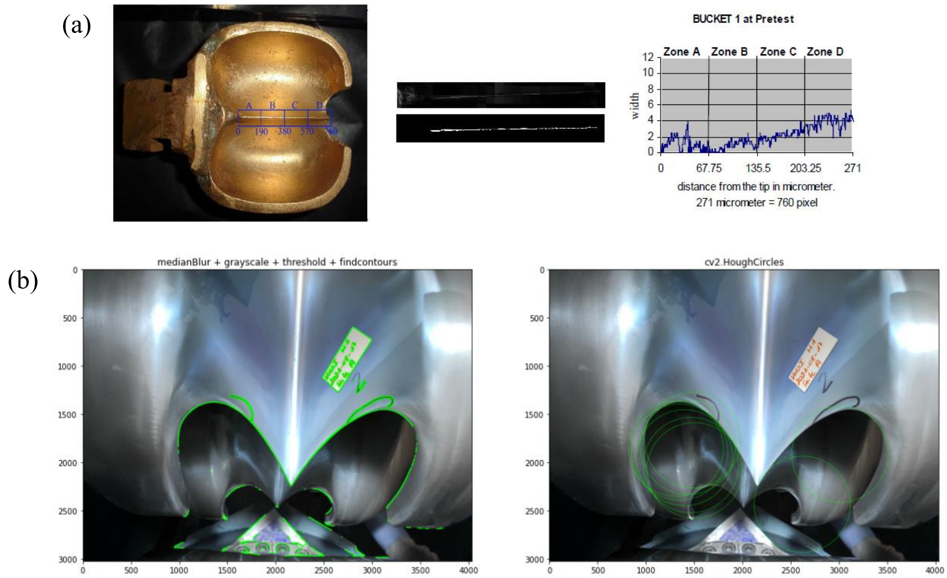

Figure 9. Image processing techniques for measurement erosion in Pelton turbines. a) Developed in MATLAB. b) Developed in Python [15, 42].

3. Maintenance of Pelton turbines

Proper maintenance of a Pelton turbine depends on physical condition, age of the asset, level of technology installed, operating restrictions, and the maintenance required [45] as shown in the flowchart in Figure 10. However, one of the principal factors is the way how it is managed in the operation, which each company owner and the electrical system required to carry out in every powerplant. The researched as well as tailored maintenance methodology such as Reliability Centered Maintenance (RCM) helps to have a better operating factor if they are well implemented [46, 47].

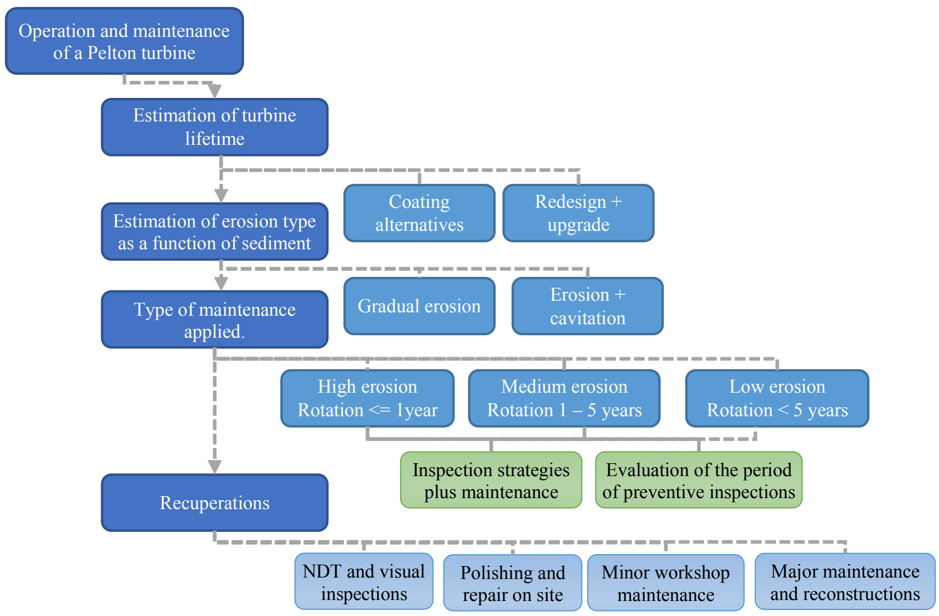

Figure 10. Evaluation criteria for the type of operation and maintenance of a Pelton turbine.

Welding is a widely used technique for the recovery of the profile of an eroded Pelton turbine. The considerations for the estimation of the operation time between each maintenance depend on an economic evaluation concerning the amount of erosion, the cost of maintenance, and the risk assumed. In addition, for an estimation of the overall life of the Pelton turbine exposed to sediments, the amount of erosion in the turbine, the profile recovered by welding, and subsequent heat treatment are needed. These criteria are also necessary for an economic evaluation of improvements like coating or sediment trap capacity.

3.1. Inspections

Inspections depend mainly on the type of wear that the turbine possesses. It may take several hours for the inspection because of the complexity of the hermetic seal installation in the turbine chambers and the assembly of structures which greatly depend upon the scope of the technical person authorized to inspect the critical section of the turbine [48].

3.1.1. Hydropower plants with low sediment load

The inspections, for evaluation of the condition of the turbine, are carried out using visual inspections technique and/or non-destructive tests (NDT). With the low sediment concentration, inspection is mainly done to detect the beginning of fatigue fractures and the advancement of the erosion trend. These inspection activities need to be carried out when the powerplant is in a complete stop state. Hence, they are normally done in seasons of low water availability to reduce the economic impact on energy production and the income from the availability of the unit in the system.

3.1.2. Hydropower plants with high sediment load

In hydropower plants with high sediment load, measurement, and inspection are carried out for the evaluation of the severity of erosion. The erosion phenomenon accelerated in the rainy seasons forcing the shutdown of units and resulting in the reduction of revenue.

3.2. Prevention of failures methods

The control of sediments and their management in Pelton turbines has been extensively studied for reducing their passage through the turbine [8]. The measurement of sediments passing through power plant facilities becomes more important nowadays and it can be periodical and online [13]. There are some points for the locations for online systems for measurement and monitoring of sediment in the powerplant with Pelton turbine as is shown in Figure 11.

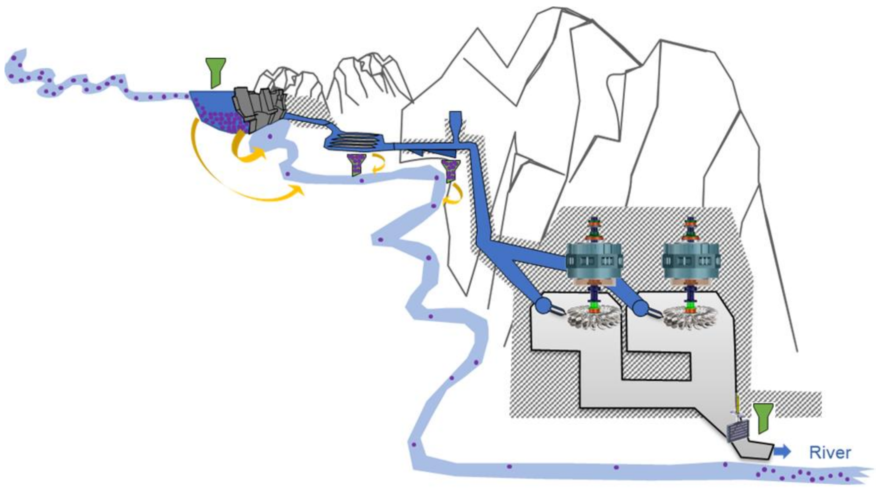

Figure 11. Diagram of some points for the locations of online system measurement of sedimentation in a typical Pelton hydropower plant.

The principal online factors to be measured are the suspended sediment concentration (SSC) [49] and its particle size distribution (PSD). Moreover, the combined dynamic imaging analysis (DIA) with modern equipment for the measurement of the size and shape of sediments is supposed to provide good results [50].

3.3. Coating on Pelton turbines
Coating in Pelton turbine buckets is the process of spraying hard ceramic material for its durability. There are several types of materials as well as processes used for coating Pelton turbines [10]. These techniques have been applied since the 1980s and have had good results in the reduction of erosion in many power plants worldwide [51]. But on the other hand, in some sites, the coating could not withstand a single rainy season as well. For instance, bad performance of coating was observed in Duck Canyon HPP at Ancash in Peru and Khimti HPP in Nepal. The eroded surface of the turbine from the powerplant is shown in Figure 12. Because of the passage of 7345 tons of sediments, the coated turbine of this power plant operates for merely 1680 hours with an average of 30.15 MW.

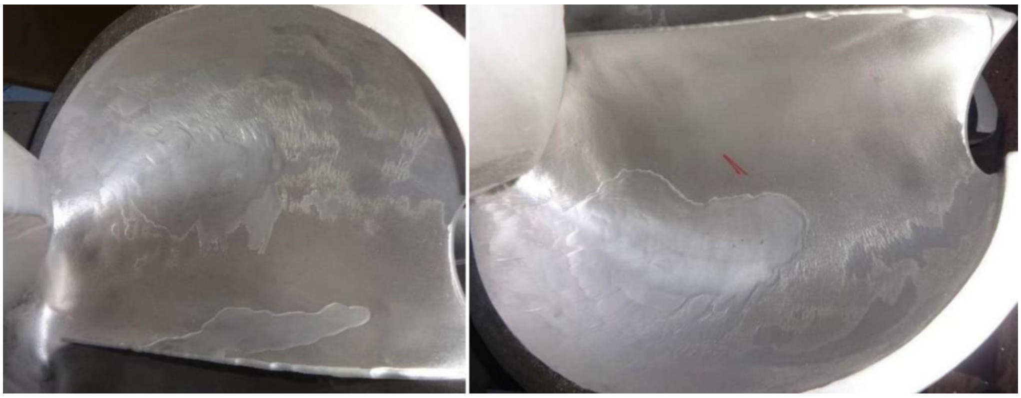

Figure 12. Erosion on the coated turbine in Duck Canyon HPP, at Ancash Peru (42MW, 380m).

4. Repairs of a Pelton turbine
The repair of the turbine generally depends on the type of maintenance carried out on each plant. It can be preventive, corrective, condition-based, or new maintenance approaches that are being customized for the power plant. The turbine is one of the main assets of the hydropower plant and in case of its failure, it can generate a significant impact on the integrity of the plant or the repair time which has a direct impact on income generation. Vibration, for instance, is measured with online systems which helps to detect the fault in the turbines and its impact on their operating conditions [48]. The maintenance of the turbines can be done on-site or by removing them and transferring them to a specialized workshop.

4.1. On-site repair
Minor maintenance works can be carried out on-site such as roughness polishing which reduces its wear exponentially. In addition, minor repair works is carried out for small cracks or wear that normally occurs outside the bucket root. This minor maintenance can be carried out after the inspections, to reduce the inoperative time. It is related to several factors such as water availability, turbine integrity, system requirement for standby, annual maintenance of all components, estimation of erosion on turbines, and season. However, the most predominant one corresponds to the evaluation of business profitability according to the methodologies or forms of maintenance used in each company. With the help of vibration monitoring, failures can also be analyzed to generate preventive models [16].

4.2. Workshop repair
For the case of major repairs such as welding work for replacement of parts damaged by erosion, repair of major cracks, or inspection in greater detail, it is necessary to remove the turbine and repair it in

specialized workshops. In such cases, the replacement of the turbine takes more time due to the maneuvers that should be performed for the heavy-weight turbines and the adjustment of their fastening elements.

5. Recuperation of Pelton turbine

The runner repair process depends mainly on how much the bucket has eroded. It can range from a simple polishing of the surfaces to completely regenerating the eroded surface of the buckets, as shown in Figure 13. The process needs to have control of temperature and follow procedures according to each runner. This uses lower temperatures to avoid changes in the structure of the base material. The use of subsequent heat treatments is always predominant to recover the mechanical properties exposed to temperature [52, 53].

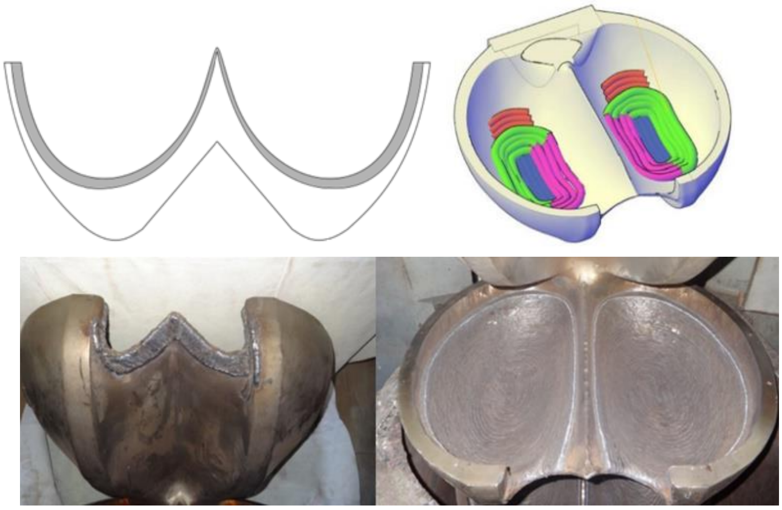

Figure 13. Weld filler process in a bucket on a Pelton runner.

The recuperation process of a Pelton turbine has many steps, beginning with the erosion inspection, and ending with static balancing, transportation, and proper storage. The main steps during the process are welding, grinding, and various heat treatments as shown in Figure 14 in the specialist workshop, or even automatized, depending on access to the workshops.

Figure 14. Main steps in the recuperation of the Pelton turbine by the welding process

6. Calculation of the lifetime of a Pelton turbine

Currently, there is no standard or established method to estimate the lifetime of a turbine [54]. The references are the guarantees that are received with the new Pelton turbines which generally include manufacturing faults and have a validity for a few years only. Similarly, World Bank's suggested lifetime evaluation is 10 years [55]. Turbines operated in water with low sediment concentration can last up to 50 years or more. Sometimes turbines operating in sediment-laden rivers with high concentrations have lasted more than 20 years. However, there are some cases of failures where turbine runners lasted less than a year.

Asset management practiced on a Pelton turbine considers and analyzes the business requirements, design, acquisition, operation, maintenance, modifications, and final disposal [56]. For this, an important factor is maintainability and its projections according to the sediment condition are important as depicted in Figure 15. The maintenance of a Pelton turbine involves visual inspections, non-destructive tests (NDT), on-site maintenance, and major maintenance with partial or complete repairs.

Another important point in consideration during lifetime evaluation is the management of all the components of the hydroelectric plant and the entire project, to have a complete overview of the financial strategies that are used [57].

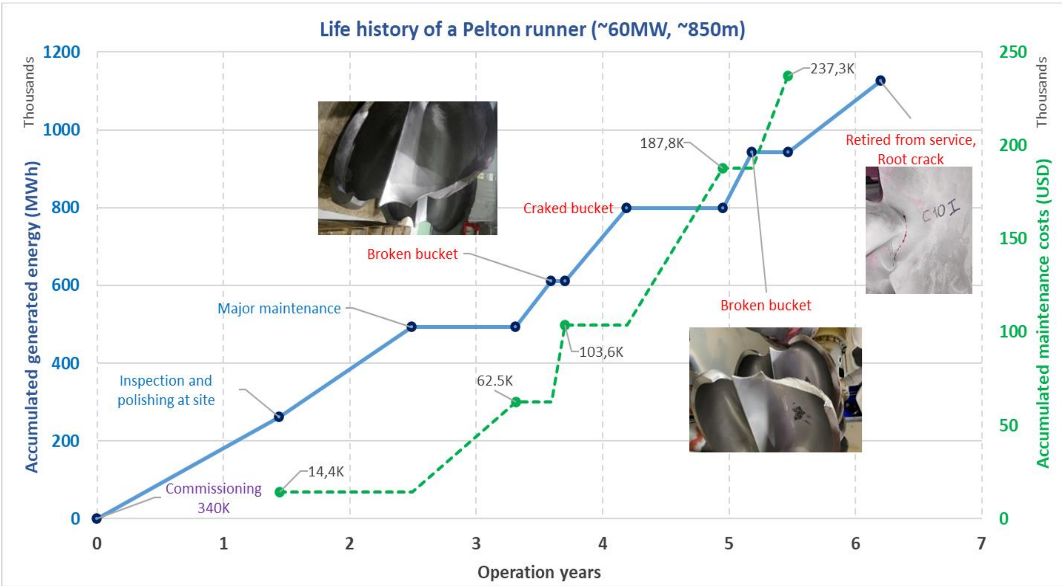

Figure 15. The life cycle of a Pelton turbine, from its commissioning to retirement in Peru.

Lifetime evaluation also considers the maintenance of the average life of the components. If there is a need for major maintenance or replacement at some point, the financial evaluation of projects is carried out with the help of *Net Present Value* (NPV) in addition to other methods such as the *Internal Rate of Return* (IRR) or the *Payback Period* [58].

The calculation of the NPV using the *Capital Asset Pricing Model* (CAPM) [48] required the *Weighted Average Cost of Capital* (WACC) which has a component called *Country Risk Premium* (CRP) [59]. CRP of the countries with high hydraulic potential in Pelton is also high [60] resulting in the WACC being high. For example, in Nepal, the hydroelectric potential is 83 GW [61] and only 2.1GW has been developed [62], which represents 2.5% of its capacity, and the CRP is 11.5% [63]. Therefore, the WACC is higher [58] which is between 15.3% and 20.8% depending on the external or internal origin of the capital [63]. In Nepal, the expected lifetime of a hydroelectric plant and its components including civil works could only be 18 years if these factors are considered.

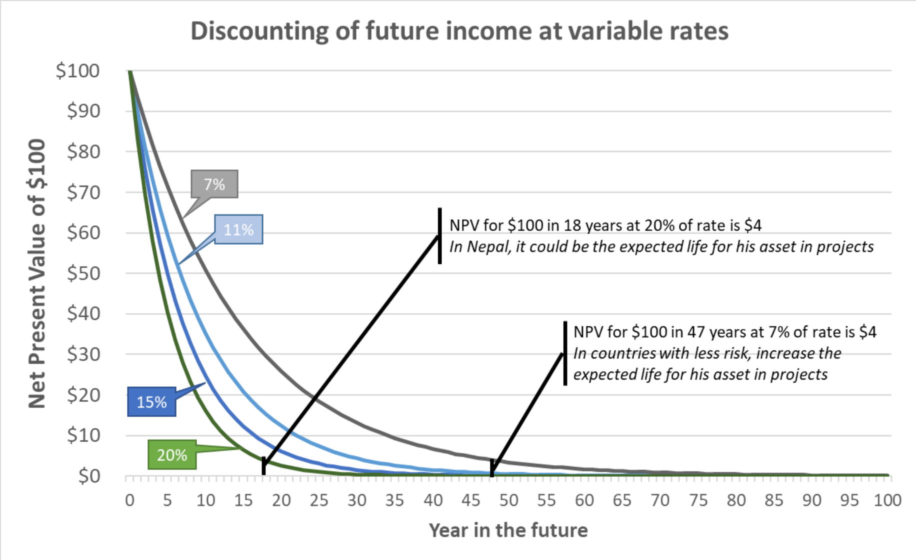

Figure 16. Graphical representation of the net present value of future income in different weighted average costs of capital.

The evaluation of the lifetime of the turbine carried out considering the project's expected life is different from project to project. In Figure 16, we can observe that the value of return on investment of a project, with a WACC rate of 20% has a net present value of 4% of the investment after 18 years. On the other hand, with the WACC rate of 7%, the same decrease in the value (i.e., 4%) will take 47 years. Therefore, it is suggested to evaluate the hydropower projects for economically stable countries with long-term years. While for the projects located in countries with high-risk country premiums, short terms evaluation methods should be used [57].

The calculated financial lifetime of a Pelton turbine should consider the location and the WACC of the hydropower plant including the cost for preventive maintenance as well as refurbishment/replacement according to the exposure of sediment loads. The erosion of the turbine is one of the main factors that must be calculated to forecast what type of maintenance is needed for the hydroelectric power plant.

7. Conclusions

Sediment erosion in the turbines operated in sediment-laden water is inevitable. Many investigations have been made to understand the flow behaviors and the effect of sediments on the performance of the turbine. Better turbine design and increased resistance of materials used for turbines in modern days are contributing to the mitigation of sediment erosion. However, a comprehensive approach is required to reduce its impact on such projects. Recently, state of art techniques like FEM and CFD are used to study sediment erosion phenomenon and its effect evaluation not only on the performance but also on the overall lifetime of the turbine. Similarly, image analysis is being utilized for estimating the flow behaviors, in addition to the detection of cavitation and measurement of wear using various processing tools with good results. Further, the lifetime estimation of a Pelton turbine is equally important which mainly depends upon the operation and maintenance strategy used along with the sediment erosion tendency. Although many investigations were made in understanding, evaluating, and forecasting the sediment erosion in Pelton turbines, clear and concise results are yet to be achieved. Hence, more study needs to be directed towards quantifying sediment erosion on Pelton turbines using modern tools and techniques along with machine learning techniques. Furthermore, proper maintenance strategy and methods need to be investigated for the proper financial estimation of the power plant in general.

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