PAPER • **OPEN ACCESS**

Application of hydro-abrasive erosion model from IEC 62364:2019 standard in Francis turbines

To cite this article: N Acharya *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1079** 012008

IOP Conf. Series: Earth and Environmental Science 1079 (2022) 012008 doi:10.1088/1755-1315/1079/1/012008

Application of hydro-abrasive erosion model from IEC 62364:2019 standard in Francis turbines

N Acharya[1*], S Gautam[2], S Chitrakar[2] C Trivedi[1] and O G Dahlhaug[1]

[1]*Waterpower Laboratory, Department of Energy & Process Engineering, Norwegian University of Science and Technology, NO-7491, Trondheim, Norway*
[2]*Turbine Testing Lab, Kathmandu University, Dhulikhel, 45210, Nepal*
**Corresponding author (nirmal.acharya@ntnu.no)*

Abstract. Hydro-abrasive erosion in hydraulic turbines is critical and one of the prominent issue due to its association with maintenance costs and production losses in the hydropower plant. IEC 62364:2019* standard guide focuses mainly on hydroelectric powerplant equipment and provides the standard on particle abrasion rates on several combinations like operating conditions, component materials properties, water quality among many factors. With the consideration of different critical parameters, a theoretical model of abrasion rate on hydraulic turbines is proposed by IEC 62364:2019. Present study is conducted to elucidate the several terms used in the theoretical model of abrasion rate for Francis turbine as per the guidelines. The work has taken account into run-off river (RoR) hydropower plant consisting of Francis runner operating in sediment laden rivers in the Himalayan area. Theoretical expected erosion depth for runner inlet, runner outlet, guide vanes facing plates and labyrinth seals is calculated. Characteristic velocities of runner (W_{run}) and guide vanes (W_{gv}) were estimated to be 32.26 m/s and 35.05 m/s respectively. Particle load was calculated based upon the sampling data available from the site. Measurement data from field observation during overhauling was used for comparison with the data calculated from empirical relation. For 229 hours operation of turbine, observed abrasion depth varies from 8.1 mm in guide vanes to 1.5 mm in labyrinth ring corresponding to calculated values of 7.53 mm and 1.89 mm for same components. Results shows good correlation among calculated values from IEC and measured values from the site. An optimized solution can thus be devised based on the evaluation of hydro-abrasive erosion along with energy production and maintenance expenses.

*IEC 62364:2019. Hydraulic machines - Guidelines for dealing with hydro-abrasive erosion in Kaplan, Francis, and Pelton turbines. Edition 2.0 (March 2019) International Electrotechnical Commission, Geneva, Switzerland [1]

Keywords: Abrasion depth, Erosion, Francis turbine, Hydropower, IEC 62364

1. Introduction

Hydropower is a reliable and versatile source of clean energy production across the globe. Modern hydropower plants are focused on providing essential energy, storage, flexibility and mitigating climate impacts as well. Hydropower sector generated a record 4,370 terawatt hours (TWh) of electricity in 2020 with a regional production of 2,141 TWh in Asia and Pacific and 690 TWh in South America alone [2]. Even though with such huge prospects and growth of hydropower sector globally, power plants located in regions such as the Himalayas in Asia, the Andes in South America, and Pacific coast are mostly prone to hydro- abrasive erosion problems which has been a major challenge [3]. It has been estimated that approximately 20%-25% of total hydropower potential in Asia and South America is affected by erosion problem. This problem is more prominent in run-of-river plants where there is no or limited amount of storage for suspended particles settlement [4]. Large sediment concentration with higher percentage of hard minerals such as quartz and feldspar affect exposed hydromechanical components.

Sediment causes significant erosion resulting reduced efficiency over time, huge operation and maintenance cost along with undesired shut-down causing loss of valuable energy generation. Continuing operation above 1500-3000 ppm sediment concentration can damage the turbine components beyond repair, hence skyrocketing cost. Literature [5] suggest that if the power plant is operated for a period of about 10 minutes with sediment concentration of around 24,500 ppm estimated cost of repair reached about ten times higher than the generated revenue during that operation. One of the earlier research revealed that powerplant's electric output at design discharge was dropped by about 10%, corresponding to an absolute efficiency reduction of about 8% within one monsoon season [6]. Similarly, two successive thermodynamic efficiency measurements carried out in one of the powerplant from Nepal at interval of 11 weeks in monsoon season shows the average loss of efficiency as 4% [7]. Petrographic analysis identifies the mineral content for the sediment load. It usually comprises the description of the macroscopic aspects of the sediment, such as fabric, colour, grain size, and other relevant characteristics that may be visually observed in hand specimen. It also helps in the identification and description of microscopic characteristics of the studied material in thin sections such as mineral composition, texture and grain size. Petrographic analysis is considered as an important tool during the planning phase of hydropower plant. Assessment should be done to quantify hydro-abrasive erosion and its impact during operation. Based on such assessment, optimized solution can be devised considering investments, energy production and maintenance cost.

International Electrotechnical Commission (IEC) gives guidelines for dealing with hydro-abrasive erosion in hydro-turbines in IEC 62364:2019 [1] with the consideration of known factors contributing to this phenomenon. Hydro- abrasion is generally determined in terms of loss of mass from the wetted passage of turbine over a known period of time. IEC 62364:2019 provides guidelines for presenting data on hydro-abrasive erosion rates with combination of parameters including operating conditions, component materials and properties, water quality in hydro turbines.

As a large part of remaining global hydropower potential falls in areas with high sediment yields, abrasive erosion issue will be increasing worldwide. Since every hydropower plant is a tailored project, a trade-off is essential among several factors. There is the possibility of designing unit which is more resistant against hydro-abrasive erosion, but it might impart adverse effects on other aspects such as efficiency, vibrations, and cavitation performance. A good understanding among all HPP stakeholders such as investors, designers and consultants, component manufacturers, measuring equipment suppliers and plant operators is hence essential for the contribution to energy and cost-efficient usage of global hydropower potential.

2. IEC 62634:2019 abrasion rate model

IEC 62364:2019 aims to develop guidelines for methods of minimizing hydro-abrasive erosion in hydro turbines based on experience data.With the consideration of different critical parameters, a model for hydro-abrasive erosion depth in a Francis turbine is proposed by IEC 62364: 2019, as shown in equation 1.

$$S = W^{3.4} \cdot PL \text{ x } K_m \text{ x } K_f / RS^p \quad (1)$$

where, S is the numerical value of hydro-abrasive erosion depth in mm.

Characteristic velocity W is unique for each machine component and is used to quantify hydro-abrasive erosion damage. Similarly, PL variable is introduced in the equation to find a simple and reasonably accurate estimate of the time integral. It is used to quantify the particles that pass through the turbine which is related to the hydro-abrasive erosion potential in a certain period. PL integrates particle concentration (C), hardness factor ($K_{hardness}$), size factor (K_{size}) and shape factor (K_{shape}) over time.

$$PL = \int_0^T C(t) \text{ x } K_{size}(t) \text{x } K_{shape}(t) \;\; K_{hardness}\,(t)dt \quad (2)$$

$$\approx \sum_{n=1}^{N} C_n \text{ x } K_{size,n} \text{ x } K_{shape,n} \text{ x } K_{hardness,n} \text{ x } T_{s,n} \quad (3)$$

The details of the terms used in above equations are presented in table 1.

Table 1. Terms, definitions and symbols used in IEC 62364 standard [1].

Symbol	Term	Nomenclature/Definition	Unit
C	Particle concentration	Mass of all solid particles per volume of water-particle mixture	kg/m^3
K_f	Flow coefficient	Coefficient characterizing abrasion with flow around each component	[-]
$K_{hardness}$	Hardness factor	Factor relating abrasion with the hardness of abrasive particles	[-]
K_m	Material factor	Factor relating abrasion with material properties of the base material	[-]
K_{shape}	Shape factor	Factor characterizing abrasion with shape of the base material	[-]
K_{size}	Size factor	Factor characterizing abrasion with size of the base material	[-]
PL	Particle load	Integral of modified particle concentration over time	$kg\ h/m^3$
RS	Turbine reference size	For Francis turbine, it is the reference diameter	m
P	Size exponent	Exponent that describes size dependant effects of hydro- abrasive erosion while evaluating RS	[-]
S	Hydro-abrasive erosion depth	Depth of material removed (measured perpendicular to the original surface) component due to hydro-abrasive erosion	mm
T_s	Sampling interval	Time interval between two samples for determination of abrasive particles in the water	h
W	Characteristic velocity	Relative velocity between the abrasive particles and turbine parts [8]	m/s

3.Methodology

3.1. Details of reference HPP

Francis turbines cover the high head range of reaction turbines, which will get the most serious damage from sand erosion due to high velocities and accelerations [9]. The work has taken account into run-off river (RoR) hydropower plant consisting of Francis runner operating in sediment laden rivers in the Himalaya area. Table 2 shows the details of considered hydropower plants for this study.

Table 2. Details of reference HPP.

Name of plant, location	No. of Units	Rated power/Unit (MW)	Head (m)	Discharge (m^3/s)	RPM	Speed no.
Bhilangana-III HPP, India	3	8	207	4.33	750	0.32

3.2. Petrographic analysis of sediment from reference HPP

Petrographic studies from the reference HPP show sediment constituting loose grains of coarse sand to fine silt and clay size [10]. It varied in color from dark grey to dirty white. Identifiable minerals included quartz, mica (muscovite and biotite), feldspar, hornblende, magnetite, and mica fragments. Most of the quartz grains were angular and sub angular in shape while feldspar grains appear sub rounded. Table 3 represents different minerals identified, their corresponding hardness (as per Moh's scale). Only the minerals with Moh's hardness scale above 5 are included in the table as these minerals are mainly responsible for hydro-abrasive erosion in turbine components.

Table 3. Mineralogical distribution (%) of sediments from reference HPP.

Minerals	Moh's hardness scale	Composition in percentage (%)
Quartz	7	75-77
Feldspar	6-6.5	7-9
Hornblende	5.5	1-2
Magnetite	5.5-6.5	3-4

3.3. Determination of characteristic velocity

Characteristic velocity (W) estimation is done with the main data and dimensions for a specific turbine. The value of characteristic velocity for different components of the turbine is provided by the manufacturer generally but if this is not the case, figure 1 provided by IEC 62364 is used for estimation of approximated value.

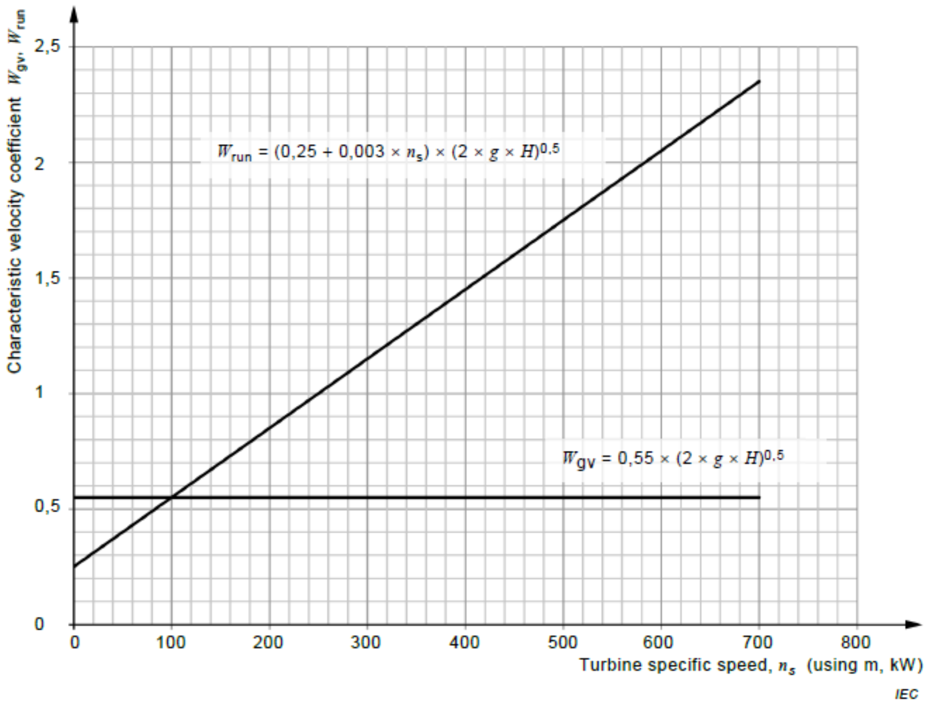


Figure 1. Estimation of characteristic velocities in guide vanes and runner.

4. Results and discussions

4.1. Calculation of total amount of erosion in B-III unit

Theoretical expected erosion depth for runner inlet, runner outlet, guide vanes facing plates and labyrinth seals for B-III unit is calculated. Referring to Table 2, specific speed (n_s) for the unit is calculated to be 85.4 based upon equation 4.

$$n_s = \frac{n\sqrt{P}}{H^{5/4}} \tag{4}$$

Characteristic velocities of runner (W_{run}) and guide vanes (W_{gv}) is estimated from Figure 1 as depicted in equations 5 and 6 respectively.

$$W_{run} = (0.25 + 0.003 \text{ x } n_s) * (2 * g * H)^{0.5} = 32.26 \text{ m/s} \quad (5)$$

$$W_{gv} = 0.55 * (2 * g * H)^{0.5} = 35.05 \text{ m/s} \quad (6)$$

Guide vanes and runner are made up of martensitic steel i.e CA6NM or 13Cr4Ni [11] and hence value of material factor (k_m) is taken as 1.

Flow coefficient (k_f) and size exponent (p) for the various components are referred from Table 4.

Table 4. Determination of K_f and p for components.

Components	Flow coefficient (K_f)	Exponent p (for RS)
Guide vanes	1.06×10^{-6}	0.25
Facing plates	0.86×10^{-6}	0.25
Runner inlet	0.90×10^{-6}	0.25
Runner outlet	0.54×10^{-6}	0.75
Labyrinth seals	0.38×10^{-6}	0.75

Total wear for all the components is calculated based on equation 1 and shown in Table 5.

Table 5. Calculation of abrasion depth for all components of B-III HPP.

Components	W (m/s)	Abrasion depth (S, mm)
Guide vanes	35.05	7.53
Facing plates	35.05	6.11
Runner inlet	35.05	6.39
Runner outlet	32.25	2.69
Labyrinth seals	32.25	1.89

4.2. Comparison of erosion pattern observed with the calculated value

Abrasion depth was calculated for the components from B-III HPP as described in the previous section. Similarly, erosion pattern was observed, and measurements of erosion area were done during the process of maintenance. Measured values on a component surface varies significantly but IEC 62364:2019 does not have exact details about the value to be considered, for example maximum, minimum or average value. However, maximum value was used during comparison for this work.

Figure 2 shows the comparison of abrasion depth for calculated and measured values for various turbine components. Bar chart shows good correlation among calculated values from IEC and measured values from the site. Abrasion depth for guide vanes and runner outlet was slightly under-predicted by calculation. The discrepancy for this might be pressure difference between two sides of guide vane which varies with flow. For the runner outlet region, it can be explained with part load (PL) condition. At PL there are two phenomenon which influence hydro abrasive erosion. First one is that the average velocity will decrease with low discharge. Another one is that flow distribution will lose uniformity increasing degree of turbulence. These two phenomena will influence hydro abrasion in opposite way but considering turbulence factor will be dominant, erosion will increase. This influence is disregarded during calculation; hence abrasion depth might be underpredicted at runner outlet. For other components like facing plates, runner inlet and labyrinth seal, there is slight difference in two values.

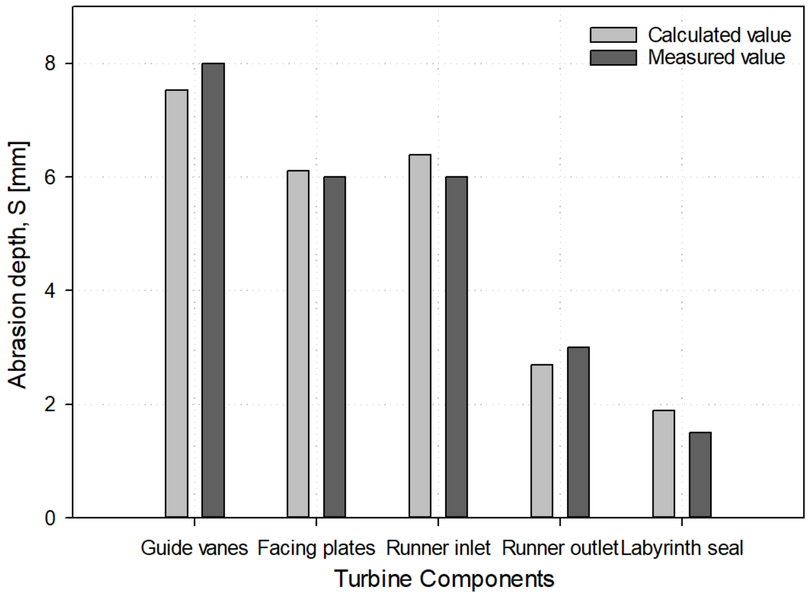


Figure 2. Estimation of abrasion depth in turbine components.

Turbine internals were eroded even the machines were operated for around 50% period during monsoon season. Figure 3 presents photographs showing hydro abrasive erosion in different components. Figure 3 is the runner inlet which shows erosion in inlet side band periphery as shown in region 1 and along the blade on low pressure side as in 2. Similarly, region 3 shows erosion along the inlet blade edge from band side and region 4 is for area-wise erosion pattern diagonally. Pit formation can be observed at runner outlet which is encircled in one blade in figure4. Severe erosion observed mainly at inlet near hub- shroud region can be related to the vortices which travels from clearance gaps and hits it [12]. Similarly, erosion observed towards trailing edge of runner is due to the vortices leaving outlet with high relative velocity.

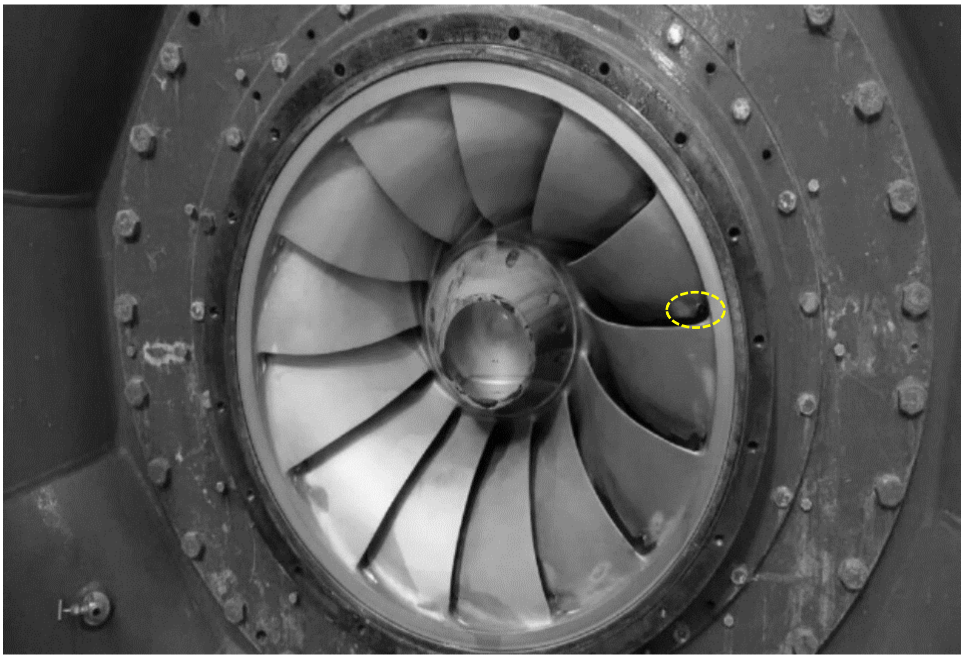


Figure 3. Hydro-abrasive erosion at runner inlet.

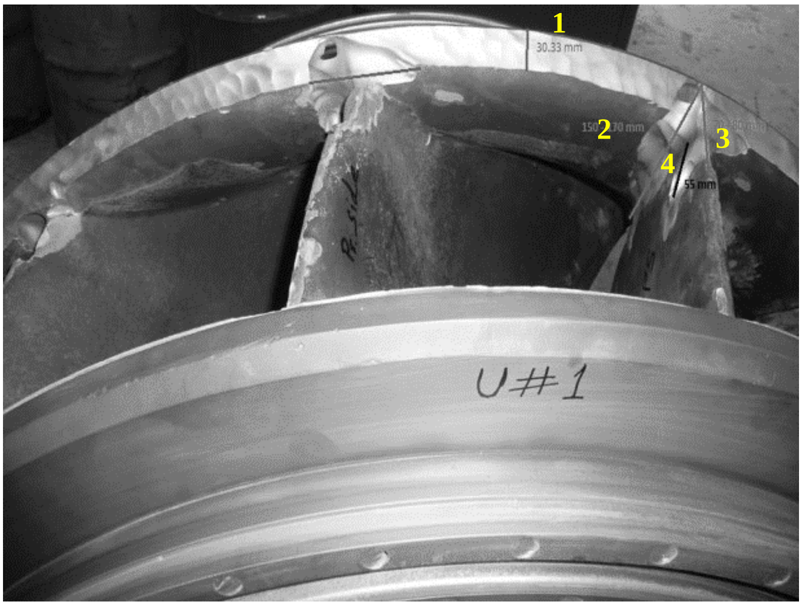
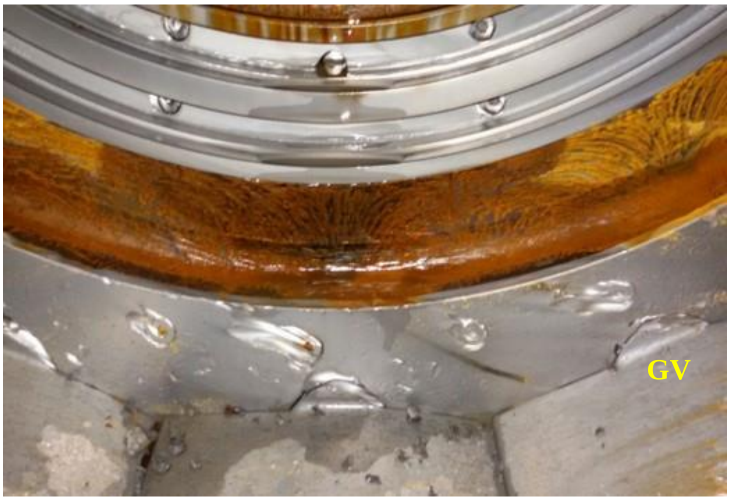


Figure 4. Hydro-abrasive erosion at runner outlet .



5(a) Head cover facing

5(b) Guide

5(c) Guide Vanes face

5(d) Upstream labyrinth

5(**e**) Downstream labyrinth

Figure 5. Hydro-abrasive erosion of other components in B-III HPP.

Figure 5 (a) shows the erosion pattern in head cover facing plate with GVs. Similarly, GV bottom shaft is severely eroded at circumference as shown in figure 5 (b). Erosion in this area is due to the cross flow or leakage flow inside the clearance gap from one side to another [13]. Figure 5 (c) shows the severity of erosion on GVs face as well. Labyrinths have been eroded throughout the curvature which starts from the top side and ends at discharge side. Downstream labyrinth shows erosion all over the ring with depth varying from 1.5-3.5 mm as seen in figure 5 (e).

5. Conclusions

Improved turbine design and increased resistance of turbine materials in modern days have been contributing to the mitigation of hydro-abrasive erosion. However, a comprehensive approach is required to reduce its impact in sediment laden projects. All possible influencing parameters and their impact should be considered. A precise prediction of hydro- abrasive erosion can help to develop proper guidelines concerning operation mode of turbines in sediment laden areas to increase the timespan of components. Starting from improving sand trap and flushing systems to optimal design and material properties of hydromechanical components should be considered. This research work is directed in explanation and calculation of terms used in the theoretical model of abrasion rate for Francis turbine in IEC 62364:2019 guidelines based on the data from reference site. Characteristic velocity for the runner and guide vanes was estimated to be 32.26 m/s and 35.05 m/s respectively. Particle load was calculated based upon the sampling data available from the site. Abrasion depth of various components for one unit was calculated as per IEC abrasion equation. Measurements of abrasion depth in various components were conducted in the site during shut down. Discrepancies in depth value for the same components were calculated and presented as shown in figure 2. For 229 hours operation of turbine, observed abrasion depth varies from 8.1 mm in guide vanes to 1.5 mm in labyrinth seal. It corresponds to calculated value of 7.53 mm for guide vanes and 1.89 for labyrinth seal. Although abrasion depth formula gives a reasonable accuracy in case of Francis turbine but still it is challenging to obtain complete and exact observations. Additional observations can be added in the future for revising the hydro-abrasive erosion model to make it more comparable. More measurements from both physical model tests in laboratories and field tests from powerplants are required to validate and further develop hydro-abrasive erosion prediction models.

Acknowledgments
This work was conducted under research project FME-HydroCen. This project (No. 90148312) was funded by Norwegian Research Council and Norwegian Hydropower Industries. Authors would like to thank Bhilangana-III hydropower plant for providing us the erosion data and relevant photographs used in this manuscript.

References

[1] IEC 62364:2019 Hydraulic machines- Guide for dealing with hydro-abrasive erosion in Kaplan, Francis and Pelton turbines, International Electro technical Commission, Geneva, Switzerland, Edition 2.0 2019-01
[2] IHA 2021, Hydropower Status Report: Sector trends and insights
[3] Winkler, K, 2014 Hydro-abrasive erosion: Problems and solutions, *IOP Conf. Series: Earth and Environmental Science,* 22 052022, doi:10.1088/1755-1315/22/5/052022
[4] Kapali A, Chitrakar S, Shrestha O, Neopane H P and Thapa B S, A review on experimental study of sediment erosion in hydraulic turbines at laboratory conditions, *IOP Conf. Series: Journal of Physics*: 1266 (2019) 012016, doi:10.1088/1742-6596/1266/1/012016
[5] Bishwakarma, M B, “Research on optimum sediment exclusion”, *Waterpower & Dam Construction* 2008

[6] Felix D, Albayrak I, Abgottspon A and Boes R M 2016, Hydro-abrasive erosion of hydraulic turbines caused by sediment- a century of research and development, *IOP Conf. Series: Earth and Environmental Science* 4912200, doi:10.1088/1755-1315/49/12/122001
[7] Thapa B S, Thapa B and Dahlhaug O G 2012, Empirical modelling of sediment erosion in Francis turbines, *Energy* 41386-391, doi: 10.1016/j.energy.2012.02.066
[8] Rai A K, Kumar A, Staubli T and Yexiang Xiao 2020 Interpretation and application of the hydro-abrasive erosion model from IEC 62364 (2013) for Pelton turbines, *Renewable Energy* 160396-408, doi.org/10.1016/j.renene.2020.06.117
[9] Duan C G and Karelin V Y 2002, *Abrasive erosion and corrosion of hydraulic machinery*, Imperial College Press
[10] Report on petrographic study of silt samples 2016, Advanced Technology & Engineering Services (A division of Aimil Ltd)
[11] Sharma S, Gandhi B K and Pandey L2021, Measurement and analysis of sediment erosion of a high head Francis turbine: A field study of Bhilangana- III hydropower plant, India, *Engineering Failure Analysis*, Vol 122, 105249, doi.org/10.1016/j.engfailanal.2021.105249
[12] Gautam S, Neopane H P, Acharya N, Chitrakar S, Thapa B S and Zhu B 2020, Sediment erosion in low specific speed Francis turbines: A case study on effects and causes, *Wear* 442-443203152, doi.org/10.1016/j.wear.2019.203152
[13] Chitrakar S, Dahlhaug O G and Neopane H P 2018, Numerical investigation of the effect of leakage flow through erosion-induced clearance gaps of guide vanes on the performance of Francis turbines", *Engineering Applications of Computational Fluid Mechanics*, 12:1, 662-678, doi.org/10.1080/19942060.2018.1509806