Numerical study of sediment erosion in guide vanes of a high head Francis turbine

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Abstract. Erosion in guide vanes (GVs) has been reported from several power plants in Himalayan and Andes basins which affects the efficiency of turbine. Wear in clearance gaps (CGs) increases with the sediments passing through them resulting in increased gap size, which disturbs the flow into the runner inducing more losses. This paper investigates the flow and erosion pattern around GVs along with the leakage flow. Simulations are carried out in full GV and runner model with varying CGs with the inclusion of sediment. 3 types of clearance gaps viz., 0.5 mm, 1 mm and 1.5 mm are included and numerical results obtained are compared with the photograph of the erosion affected guide vanes. Result shows that erosion was prevalent in regions downstream of the mid-chord position inside the CG due to high pressure difference between two sides of GVs and the leakage flow induced from the pressure difference mixes with the main flow forming a vortex filament, which is driven towards the runner inlet.

Keywords: Francis turbine; sediment erosion; guide vanes; vortex; clearance gap; leakage flow

1. Introduction
Sediment transport in Himalayan rivers reaches their peak during the monsoon period which comprise quartz as a main constituent (more than 50%), along with feldspar and other hard minerals. Hard sediment constituents cause erosive and abrasive types of wear in turbine components. 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 [1].

Guide Vanes (GVs) are symmetrical or asymmetrical hydrofoils attached with shafts which act as the flow control apparatus responsible for flow governance in turbine setup. They are subjected to entering flow from stay vane and exiting flow to runner, and major physical factors such as hydrofoil profile, clearance gaps, angle of attack, presence of shafts in high velocity etc. are associated with this flow. Gaps on the passage induce leakage and other secondary flows which disturb the main flow downstream. Some researches had been done earlier for sediment erosion induced leakage flow from GV’s clearance gap in Francis turbine. Brekke [2] studied the influence of varying size of GV’s clearance gap on turbine’s efficiency in which it was observed that the clearance gap has a high influence on overall efficiency of Francis turbine. Another work showed that all sizes of clearance gap larger than 1 mm induces turbulent cross-flow which mixes with main flow and disturbs the runner inlet flow conditions [3]. Numerical analysis done to investigate the effect of leakage flow on performance of the turbine showed that the symmetrical GV profile was not suitable for best efficiency and part load conditions [4]. Similarly changing GV profile shape can get much lower velocity difference between the two sides.
with a clear improvement of leakage flow and observation of weaker and smaller filament vortex in the new design [5].

This paper focuses on a high head Francis turbine operating under 207 m nominal head and 4.33 m$^3$/s rated discharge. Petrographic study of silt samples from the site shows composition of loose grains of coarse sand to fine silt and clay which comprise of quartz & lithic fragments, feldspar, mica (muscovite and biotite), hornblende, and magnetite. Figure 1(a) and 1(b) shows the representation of GV with dry clearance and inclusion of clearance gaps representing eroded profile respectively. As depicted in figure, original width of clearance gap is $t$, which increases to $t+\Delta t$ after erosion [6]. Actual eroded surfaces are non-uniform and erratic but assumption of uniform clearance gap is done to get the general sense of leakage flow through GVs.

![Figure 1](image.jpg)

**Figure 1** (a) GV with dry clearance and (b) Eroded GV profile representation

2. Methodology

2.1. Numerical Model

2D geometry of GVs obtained from the power plant was used for the numerical work. An in-house developed code was used to produce a reference turbine, as there was limitation for the availability of design and drawings of installed prototypes. CFD simulations were carried out for 1 GV profile and 3 clearance gaps at best efficiency point (BEP). The full model of the turbine consists of 13 runner blades and 24 GVs, as shown in Figure 2. The domain was divided into 3 sub domains, GV (stationary), runner (rotating) at 750 rpm and a portion of draft tube (stationary). Full passage modelling was carried out in this study to avoid shifting of vortex filament in the interface due to mismatch in pitch angles between the domains of GVs and runner. Mass flow rate of 4330 kg/s at inlet and atmospheric pressure at outlet were chosen as boundary conditions. Designed mass flow rate of the turbine representing 100% flow was taken as BEP. SST turbulence model was used due to its robustness in predicting both near and away wall boundary flows. This numerical analysis is focused on the flow pattern around guide vane profiles with varying clearance gap corresponding to sediment erosion which would influence erosion pattern in the runner blades as well. Steady state analyses were conducted to study the leakage flow through the clearance gap and transient analyses were done to predict the true transient interaction of the flow between GV and runner blades.

2.2. Erosion Model

Sediment particles are defined as solid particles and size distribution is uniform in diameter. For this case, quartz is considered as it affects the most and hence particles are modelled based on quartz properties. Particle size and density is given and mass flow rate of sediments is obtained from the sediment data of Bhilangana-III (B-III) HEP.

Tabakoff erosion model was chosen over Finnie for the simulations as it considers more parameters and is relatively more reliable and gives more realistic erosion rate indication [7]. Tabakoff erosion model in ANSYS CFX, determines erosion rate $E$ from the following relation:
\[ E = f(\gamma)(V_p/V_1)^2 \cos^2\gamma \left[ 1 - R_T^2 \right] + f(V_{PN}) \]  

(1)

where,

\[ f(\gamma) = [1 + k_2 \cdot k_{12} \cdot \sin(\frac{\pi}{2}/\gamma_0)]^2 \]  

(2)

\[ R_T = 1 - \frac{V_p}{V_3} \sin \gamma \]  

(3)

\[ f(V_{PN}) = \left( \frac{V_p}{V_2 \sin \gamma} \right)^4 \]  

(4)

\[ k_2 = \begin{cases} 
1.0 & \text{if } \gamma \leq 2\gamma_0 \\
0.0 & \text{if } \gamma > 2\gamma_0 
\end{cases} \]  

(5)

Here \( E \) is the dimensionless mass (mass of eroded wall material divided by the mass of particle). \( V_p \) is the particle impact velocity, \( \gamma \) is the impact angle in radians between the approaching particle track and the wall, \( \gamma_0 \) being the angle of maximum erosion. \( k_2 \) and \( k_{12} \) are model constants and depend on the particle/wall material combination.

Erosion of a wall due to a particle is computed from the following relation:

\[ \text{Erosion Rate} = E \cdot N \cdot m_p \]  

(6)

Where, \( m_p \) is the mass of the particle and \( N \) is its number rate. The overall erosion of the wall is then the sum over all particles. This gives an erosion rate in [kg s\(^{-1}\)], and erosion rate density in [kg s\(^{-1}\) m\(^{-2}\)] to indicate the erosion area visually on the wall surface.

**Figure 2** Computational domain showing entire mesh and the enlarged one near guide vanes

### 3. Mesh Sensitivity Analysis

Estimation of discretization error and extrapolation values was done by using the GCI method [8]. This technique is found to be effective in predicting numerical uncertainties for the case of Francis turbines [9]. For uncertainty analysis, three mesh were created with number of elements in each mesh equal to 1.6, 4.9 and 16.7 million. Mesh refinement was done by increasing the distribution in each direction. Efficiency was chosen as monitored variable. These values obtained by the three mesh densities are
noted as $\eta_1$, $\eta_2$, and $\eta_3$, where $\eta_1$ represents the results of the fine mesh and $\eta_3$ represents that of the coarse mesh.

The fine-grid convergence index was estimated as:

$$GCI_{\text{fine}}^{21} = \frac{1.25 \eta_2^{21}}{r_{21}^l - 1} \quad (7)$$

Table 1 shows the uncertainties and extrapolated values. The numerical uncertainties in the efficiency was calculated to be 1.46% and 3.69% for the medium and fine grid densities respectively.

| $r_{21}$ | $r_{32}$ | $\eta_1$  | $\eta_2$  | $\eta_3$  | $p$ | $\eta_{\text{ext}}^{21}$ | $\epsilon_{\text{ext}}^{21}$ | $GCI_{\text{fine}}^{21}$ | $GCI_{\text{med}}^{21}$ |
|---------|---------|----------|----------|----------|-----|--------------------------|---------------------------|--------------------------|--------------------------|
| 1.78    | 1.43    | 90.11%   | 90.79%   | 89.81%   | 0.86| 89.06%                  | 0.0075                    | 0.0118                   | 0.0146                   | 0.0369                   |

4. Results and discussions
Numerical erosion model calculates the forces that acts when the particles (sediment in this case) collides with the wall where erosion rate indicates loss of material per square meter per second, and are seen as colored spots in Figure 3. Complete blue area denotes zero erosion and red areas are highly affected areas with maximum erosion intensity. Along the pressure side of the blade, erosion in observed near the trailing edge and some erosion is detected on the suction side as well in the middle portion and near trailing edge area. One of the study [2] shows that kinetic energy increases from about 10% to about 50% from guide vane inlet to the runner inlet for a high head Francis turbine which clearly indicates availability of very high accelerated flow inside the guide vane which can resulting secondary flow, aggravating the erosion problems. Figure 3 shows the turbulence erosion pattern in guide vane in which fine particles erode the GV outlet both pressure and specially towards suction side.

![Figure 3 Erosion pattern on GV (a) Pressure Side and (b) Suction side](image-url)
Erosion can also be seen in GV’s facing ends, both in the upper and lower facing ends as shown in Figure 4(a). Figure 4(b) shows the GV profile in Unit-I after 6170 hours of operation which shows similar pattern with the numerical one and Figure 4 (c) shows erosion pattern in facing plate along with GV contour which is secondary flow type of erosion which occurs in the corners between facing plates and guide vanes. More erosion was observed downstream of the mid-chord due to larger intensity of the leakage flow in this region. The high leakage flow is governed by the pressure difference between two sides of the GVs [6]. It is to be noted that in the current CFD model, the shafts have not been modeled. Erosion downstream of the shaft is more severe due to high turbulences in these regions.

Figure 4 (a) Erosion pattern in GV’s face ends and (b) Photograph of eroded GV profile and (c) Facing plates

Guide vanes consist of a small clearance gap at both ends to adjust the opening angle based on various operating conditions. In case of sediment affected power plants, hard fine particles mixed in water erode the connecting ends due to horse-shoe vortices. This erosion together with the head cover deflection due to water pressure increases the size of the gap. Leakage flow refers to the flow passing from high pressure side to low pressure side of GV inside clearance gaps as depicted in Figure 5. At high acceleration, when the sediment particles enter in to the gap, it further causes abrasion on the guide vane ends and facing plates as seen on Figure 4(b) and 4(c).

Figure 5 Leakage flow pattern as seen by velocity vectors
Amount of leakage flow can be analyzed from the velocity vectors plotted along the camber line inside the clearance gap. In an ideal case without leakage flow, flow perpendicular to camber line is zero. Figure 6 shows the fluid leaving perpendicular to the line with high velocity. This accelerated flow from the trailing edge of GV mixes with the main flow entering from GV and causes more disturbances in runner inlet. Hard sediment particles enter the clearance gap along with the fluid which have tendency to shear the walls of GV upper and lower face as well as top seal and bottom seal at a very high velocity. Earlier study [10] has showed that CG up to 0.5 mm is acceptable but as the CG increases, velocity component at runner inlet changes significantly causing local increase in relative velocity which is identified as the reason behind severe erosion at runner hub.

Figure 6 Velocity vectors inside CG

Figure 7 shows iso-surface of swirling strength obtained from transient analysis for different CGs. It is one of the methods to visualize the vortex, which represents the strength of swirling motion around local centers.

Figure 7 Iso-surface contours of swirling strength with velocity for (a) 1 mm (b) 1.5 mm clearance gaps
GV profiles with three CGs are compared at same swirling strength of 500 Hz and velocity on the vortex core to justify the comparison. It is observed that the strength of the vortices and velocity of the flow is higher for higher thickness of clearance gap i.e. with 1.5 mm CG among the three gaps studied in this paper (only 2 shown). This vortex flow tends to hit the runner inlet and move towards trailing edge at a high velocity thus aggravating the erosion problem.

5. Conclusion
Sediment erosion analysis of a turbine gives an indication of relative erosion intensity and critical zones of erosion damage of turbine components. Numerical analysis on guide vanes of B-III HEP was carried out with existing design. Erosion pattern, erosion rate density and nature of vortices originating from leakage flow were observed during the process.

It was seen that erosion pattern in GVs predicted by CFD matches with erosion in actual turbine as seen in Figure 4(b) and 4(c). Velocity vectors on the upper plane of GV shows the significant leakage flow passing from high pressure side to low pressure side as observed in Figure 5. This leakage flow disturbs the main flow causing swirl which never enters the runner channel and leaves energy unutilized. Erosion was seen mostly in regions downstream of the mid-chord position inside the clearance gap due to local separation and vortex. Secondary flow erosion might have been caused by horse shoe vortices which can be seen on facing plates along the guide vane contours as observed in Figure 4(c). Comparatively, strong vortices are generated from the guide vanes with clearance gap of 1.5 mm which might be accountable for the high erosion on runner blade inlet. In addition to gap erosion; erosion on foil surfaces causes friction drag resulting high friction losses.

Other hydrofoil profiles, angle of attack, inclusion of GV shaft, sediment size & concentration, GV opening angle should be investigated to draw the conclusion on the erosion pattern, localization and quantity. For the ease of calculation, uniform clearance gaps were considered for this case. Accurate results might be obtained from the exact or at least similar type of non-uniform gaps.

6. Future work
Numerical simulation in existing guide vanes with non-uniform clearance gaps and more accurate runner from the power-plant considering erosion phenomenon will be continued as further works. For this paper, simulations were carried out for one GV opening conditions i.e. for BEP obtained from the in-house code but other openings conditions will be considered. Most optimum shape of guide vanes with suitable hydrofoil and runner blades design will be investigated to address erosion challenges in sediment laden projects.

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