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Development of simplified model for prediction of sediment induced erosion in Francis turbine's sidewall gaps

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Abstract. Sediment induced erosion in exposed components of hydraulic turbines is a major issue in most of the sediment laden hydropower projects. Gradual removal of material can change the components profile which can lead to change in flow characteristics and compromise in the efficiency as well. Among several components in Francis turbine, this study focuses on the runner sidewall gaps to develop a numerical model for erosion prediction. A prototype high head Francis runner with specific speed of 85.4 rpm has been considered as the reference case. A simplified numerical model based on the concept of rotating disc apparatus (RDA) is conceptualized to make analogy with the gap available between runner blades and guide vanes (GVs). Fillet gaps are introduced in the model to emulate the gaps available between runner blade and GV for real case scenario. Four samples with 90° separation of each are mounted on the disc rotating at 750 rpm. Sediment size of 150 µm diameter with particle mass flow rate based on the maximum amount of sediment passing through the reference turbine is used. Numerical calculation is done in ANSYS® with Tabakoff erosion model. Results give an indication of critical zones in the gap region. Erosion pattern, rate density and vorticity are compared with the actual turbine.

Keywords: Erosion, Fillet, Francis turbine, Numerical analysis, Sediment

1. Introduction

Sidewall gaps in Francis turbine refers to the clearance region between stationary and rotary components. For hydro turbines operating with sediment contained water, sediment can enter through these gaps and erode the parent material. Due to continuous effects of abrasion and erosion, these side wall clearance region increases and consequently the leakages. This volumetric loss induces the reduction in the efficiency. The leakage flow and its consequent effect due to sediment was investigated in the studies [1-6]. This leakage flow was developed from the clearance gap region between guide vanes and top-bottom covers. At GVs the clearance region increases due to the continuous effects of erosion wear. This also increases the leakage vortex from the GV. Erosion towards the inlet of the runner is mainly due to these leakage vortices from the GV. Besides the erosion due to the leakage from GV, due to continuous interaction between sediment and turbine material while flow is escaping from rotor-stator clearance region, erosion can be observed at these locations. As sidewall gaps are the area of interest for this research work, detailed view of the flow region is shown in Figure 1. In the reference case, difference in level between guide vane width and runner height is approximately 2.2 mm which is highlighted in Figure 1. Water after leaving GV tries to escape through this gap before entering the runner blade inlet.

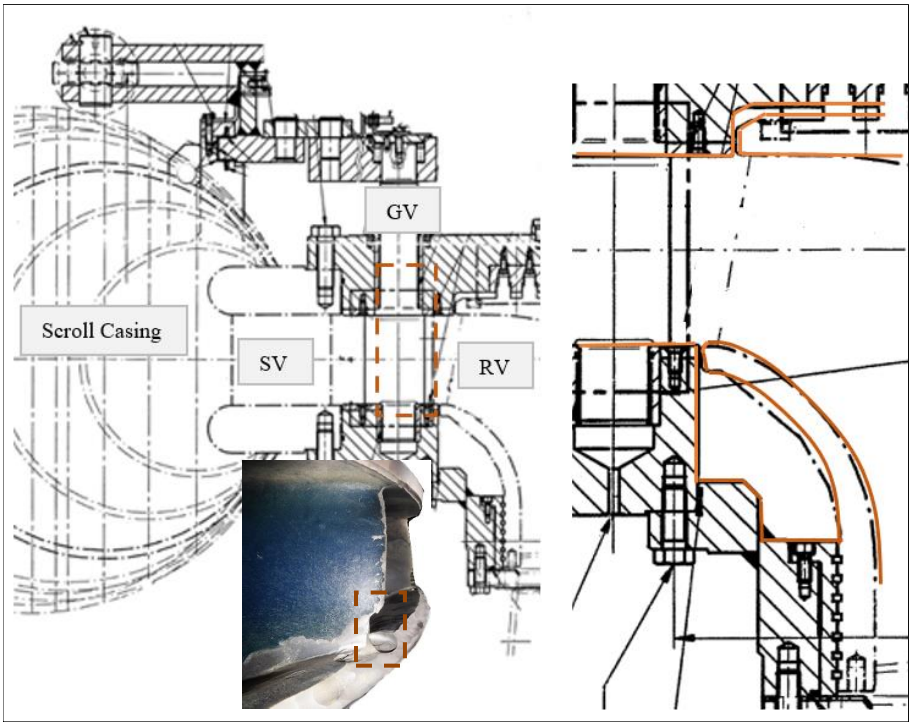

Figure 1. Cross section of reference case with the detailed view of the sidewall gaps and the section of runner from the reference site for illustration of area of interest

Wear and tear of turbine material due to sediment flow is one of the major challenges for hydropower plants operating in Himalayan regions of Nepal [2,6-11]. While past studies were limited to study the erosion at GV and runner blade of Francis turbine, erosion towards the hub and shroud region at circumferential locations were not examined at all. Some studies claimed that the erosion at overall circumference of the runner hub-shroud was due to leakage vortex. However, this hypothesis is only true at the certain locations of the runner where the leakage vortex hits directly. Figure 2 shows the oblique location of the rotating runner eroded due to sediment. This study aims to examine the cause of erosion at that location of the runner using numerical technique.

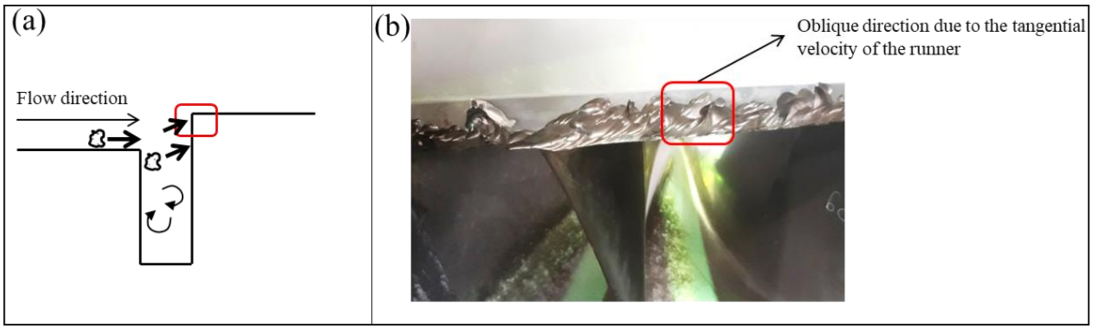

Figure 2. Effect of sediment contained flow on the turbine material (a) Nature of sediment contained flow and (b) Erosion effects towards runner band

2. Development of the reference case

Figure 3 presents the two-dimensional representation of the reference geometry presented in this study. In Figure 2(a) top view of the geometry is given that shows two specimens S1 and S2 placed at the two opposite ends of the circle. Figure 2(b) and 2(c) shows two different geometries similar in all geometrical aspects but only different with the height of the opposite ends of the gap ‘s’. This arrangement gives the basis for comparing the difference in the flow field with respect to slot gap and the difference in height ‘δh’. CAD model of Rotating Disc Apparatus (RDA) is shown in Figure 4 where specimens were mounted for experiments.

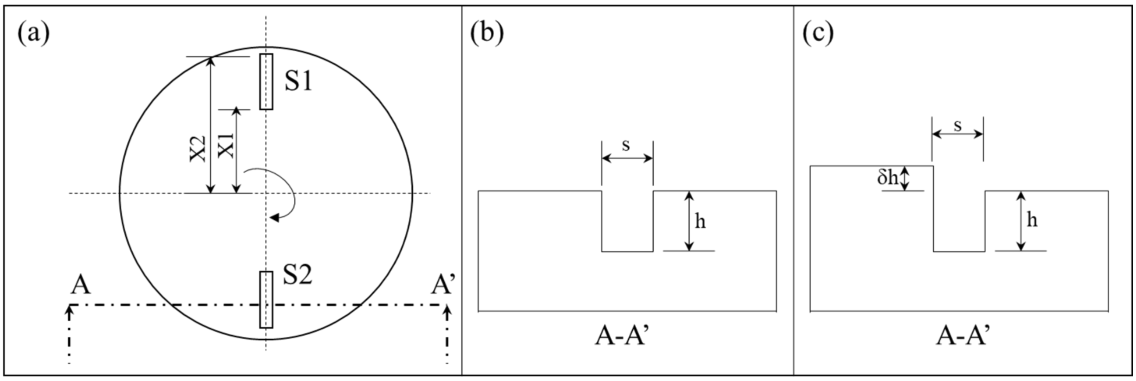

Figure 3. 2-D view of reference geometry (a) Top view (b) Section A-A’ for geometry with equal heights and (c) Section A-A’ for geometry with unequal heights

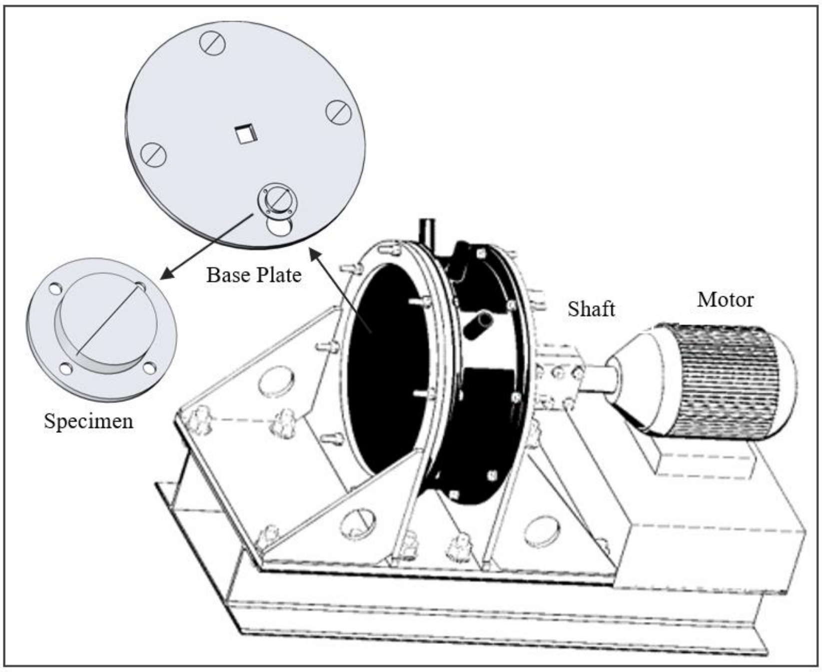

Figure 4. Experimental set up showing base plate and specimen

2.1 Numerical model and mesh

A simplified numerical model is developed that depicts the gap between the rotor-stator component. There are two different models of the gap in this study. First model has equal height of opposite to the slot gap and second model has unequal heights. The numerical model consists of a cylindrical domain, with the slot gaps in the opposite end of the cylinder exactly at 180 degrees. The 3-D geometry of the simplified model is discretized with structured hexahedral grid using ANSYS ICEM CFD. Near the wall of the gaps, boundary layer is refined to maintain the y+ less than 10. Minimum quality of the grid was less than 0.4. Numerical uncertainty in measuring pressure values at the centre of slot from medium grid to fine grid was 0.8%. Figure 5 shows the model discretized with hexahedral cells.

For the numerical study, Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations were used to model the flow field and solved using element-based finite volume method. Buoyancy model was activated in the simulation to achieve the gravity effect in the numerical model keeping the constant gravity term 9.81m/s^2. The simulations were performed using transient flow condition considering 5 revolutions of the domain at rotational speed 750 RPM. For erosion modelling, Tabakoff and Grantt erosion model was used based on the effectiveness of the numerical model from previous literatures. Sediment properties used in the numerical model are listed in Table 1.

Table 1. Sediment properties used in numerical model

S.N.	Parameters	Value	Unit
1	Density	2650	kg/m^3
2	No. of particles	5000	-
3	Shape factor	0.7	-
4	Size	150	μm

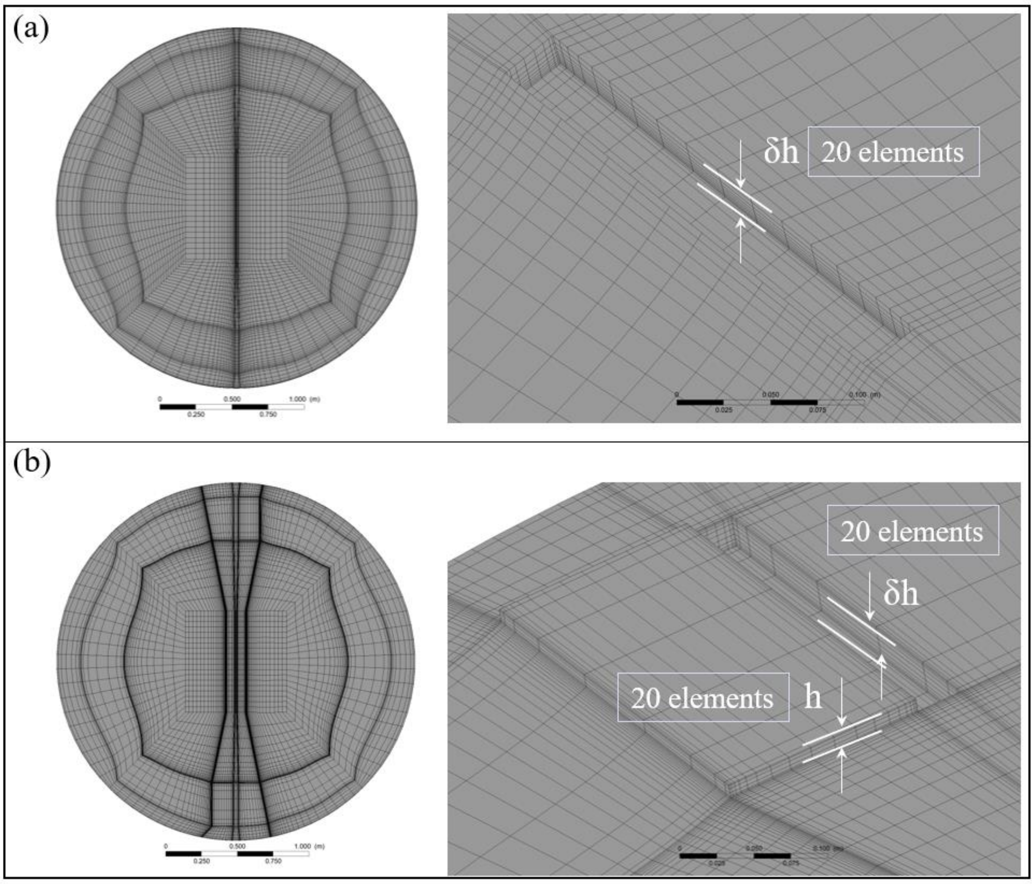

Figure 5. Mesh developed for the numerical study, (a) Fine grid for equal slot height and (b) Fine grid for unequal slot height

3. Results and discussion

3.1 Vortex formation inside slot

As shown in Figure 3, that the two opposite ends of slot are at different distance from the centre of rotation, effect of centrifugal force on the vortex formation and propagation can be observed clearly at two different ends. As the centrifugal force is the function of distance to the centre and rotational speed, the evolution of vortex can be observed from shorter radius to the greater one, where the re-circulating flow is pushed away from the centre of rotation.

In a rotating domain, the presence of a gap induces the flow disturbance. In this study a whole domain is rotating at an angular speed of 750 RPM which corresponds to the rpm of reference runner.

The presence of slots at two opposite ends of the domain, gives rise to the flow recirculation. Thus, the distinct region of flow recirculation is observed inside the slot that induces the vortex flow. In figure 6, recirculating flow is observed inside the gap and at the stepped end in the direction of rotation.

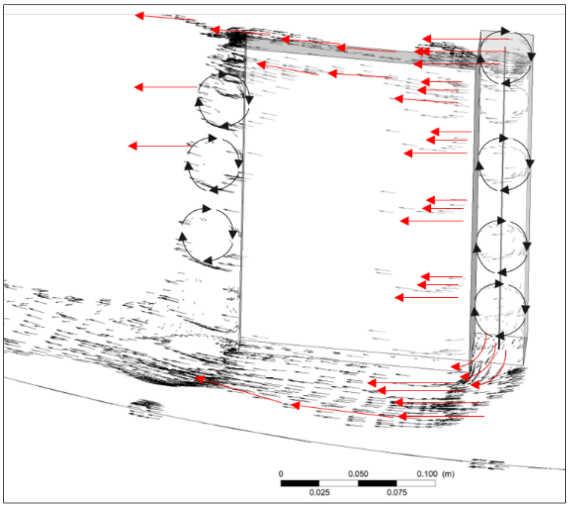

Figure 6. Velocity vector from slot

3.2 Vortex formation inside slot and sediment erosion

Sediment erosion is directly related with the corresponding flow field. Literatures [12-13] suggested that the presence of strong vortices along with sediment particle induces the severe effect of sediment erosion problem. In Figure 7, the presence of strong vortex with highest flow velocity is observed. Since, the velocity of fluid is directly related to the velocity particle and consequently the sediment erosion effect as suggested by Truscott [14], erosion problem is pre-dominant in the region corresponding the highest flow re-circulations. The erosion towards the corner of the gaps where the combined effect of centrifugal force in sediment contained flow and flow re-circulations is highest can be predicted with this nature of vortex.

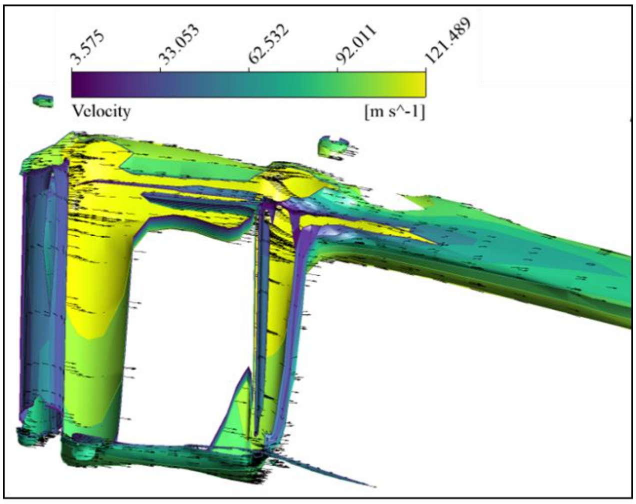

Figure 7. Velocity of fluid in the vortex inside the slot

3.3 Vorticity propagation

Figure 8 shows the intensity of vortex at the two different specimens: (i) with slot only and (ii) with both slot and height difference. For both cases, the vorticity is increasing corresponding the geometrical location i.e., increasing with the distance from the centre of the numerical domain. As discussed in previous section, this increasing vortex tendency is obvious due to higher centrifugal force acting in the working fluid at higher radius. Therefore, the region of sediment erosion can be observed due to the presence of vortices. However, in case of the specimen with slot only the intensity of vorticity was higher compared to slot and height. This is due to shifting of vortex core region at other geometrical location to that of specimen with slot only. In both the cases comparison was made assuming that the vortex core region occurs at same geometrical location. Moreover, added to the central vortex core region inside the slot the vortex flow is also observed at the stepped region. Due to this reason the erosion effects can be seen at two different locations: one inside the gap and the other towards the corner of stepped geometry due to difference in height.

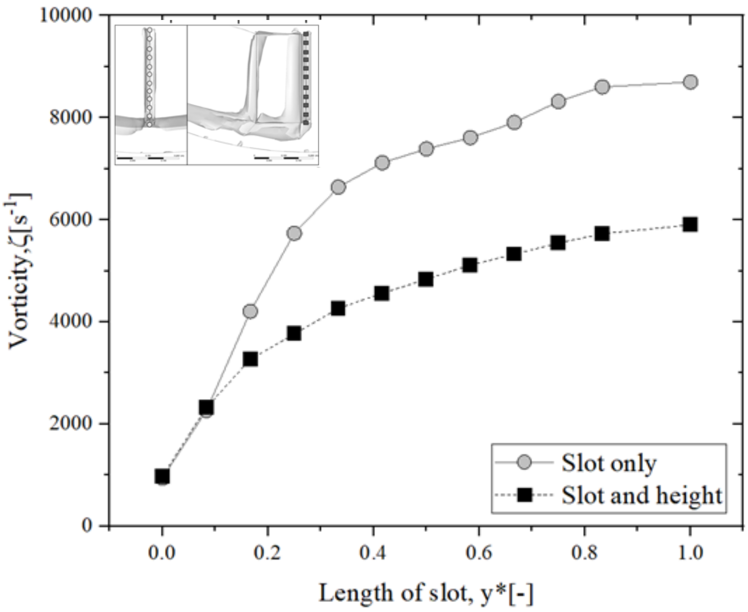

Figure 8. Vorticity distribution inside slot (X-axis shows normalized slot length and Y-axis shows the intensity of the vorticity)

4. Comparison with experimental results

A simplified test rig was developed as a part of this research to predict the sediment erosion effects due to the presence of slot gap. The rig is Rotational Disc Apparatus (RDA) developed by Rajkarnikar et. al. [15], where four different samples were assembled in a rotor-disc and rotated inside the sediment contained water.

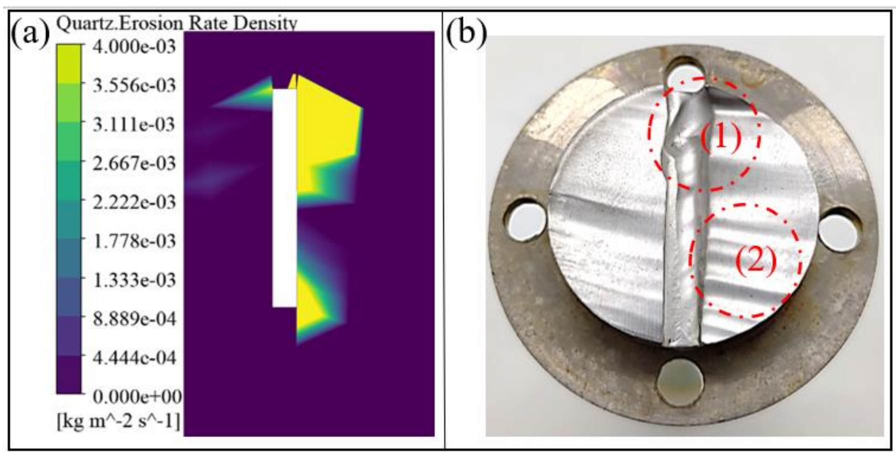

Figure 9. Result from numerical study and experiment (a) Sediment erosion predicted by numerical study and (b) Erosion predicted by the experiment for same case

Experiments were conducted at the same rotational speed as in numerical model and nearly 50,000 ppm of sediment with average shape factor 0.68 and size less than 150 μm was used inside the experimental set up. Figure 9 presents the results from both numerical study and the experiment. It can be inferred from above figure that the erosion is highest towards the opposing end of the gap due to abrasion of sediment particle. The result from experiment presented in Figure 9(b) shows two different regions of erosion. Region 1 is at the farthest end from the centre where all the vortices accumulate, has the distinct region of erosion due to flow re-circulation. In Region 2, the scaled effect of erosion at an angle less than 90 degrees to the slot length is observed. This angular region of erosion is due to the resultant effect of radial and circumferential velocity component acting in the sediment particle.

5. Conclusion

Overall, this study presented a simplified numerical model to predict the flow field inside the gap that can be related to rotor-stationary gap of Francis turbine and the corresponding sediment erosion effects. The presence of gap induces the vortices that have severe effect due to sediment contained flow. The continuous interaction between the sediment particle and the surface of material gives rise to erosive and abrasive wear.

Detailed flow physics based upon the nature of vortex development, propagation and the erosion were studied. It was found that inside the gap of a model rotating at certain angular speed, the vortex develops from lower radius, accumulates to the higher radius and leaves with high intensity. This phenomenon can be observed for both cases having equal heights between the slot gaps and unequal height. However, in the case of the model having unequal heights another region of vortex development was also observed. This can be directly related to the difference in guide vane outlet height and runner inlet height in case of Francis turbine. Finally, the numerically predicted erosion pattern was compared with the experiment. The numerical model was found to be suitable to predict the erosion effects induced by the gap.

6. Future Works

Experimental works in RDA are being continued with the variation of slot width and fillet radii as well. With these various measured set of parameters, authors expect to come up with mathematical model for prediction of erosion in the stated area of interest.

7. Acknowledgments

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