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Finite Volume Method Numerical Modelling of the Penstock Flows in Dam Intake Sector Subjected to Varying Operating Conditions with Particle Image Velocimetry Validation

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ABSTRACT

The formation of vortex and swirling in any flow structures of the hydropower dam is undesirable, as it reduced the performance of turbine as well as lowered the efficiency of hydroelectric power generation. Furthermore, it could lead to the hydraulic losses at the entrance of power intakes, the blockage at the trash racks due to entrain debris and the reduction of the working life of turbines. This paper studied penstocks flows in the dam intake section numerically. The dynamics of penstocks flows at different operating conditions were analyzed to determine the vortex formation. To access the veracity of the current proposed numerical model, a validating study based on the particle image velocimetry (PIV) experiment was conducted. It was found the discrepancy between both numerical and experimental flow velocities is 12%, implying the numerical model is well-validated and the corresponding findings are acceptable. It was found that the vortex was formed in the penstock that located at the lowest level relative to other penstocks. Furthermore, the highest pressure of 4 MPa was recorded at the bottom section of the penstock which observed vortex. This numerical work provided useful insights for the future dam reliability analysis, particularly involving penstocks and intake section.

1. Introduction

Dam is a vital water retaining structure for the hydroelectric generation as well as domestic water supply. Nonetheless, the dam failure is disastrous, as it not only causes the disruption of water and electric supplies, but also incurs large casualty and financial loss. Therefore, regular check and maintenance are necessary to ensure the regular and continuous operation of dam and the

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hydroelectric power plant. As such, the dam reliability study was conducted to investigate the structure integrity of dam and to improve performances of hydroelectric generation [1-4]. In the past literatures, the structural reliability of dam was mainly investigated from the perspectives on the interaction with fluid flow, such that the structural stress and deformation were induced by the rapid and continuous water flow throughout the dam operation [4-8]. However, these studies tend to focus on the particular dam structures. This includes spillway structure, radial gates, downstream sector and reservoir bank [4-8]. Nevertheless, there is no dam reliability study on the penstock and intake structure being conducted to date.

Generally, there are various causes for dam failures, for instance the natural disasters, poor maintenances, design error and operational induced [9,10]. Particular for the operational induced dam failure, the dam structure will sustain inevitable damages upon subjected to continuous and tedious operating conditions, such as rapid water flow. One of the possible undesirable consequence of un-optimized operating condition being the vortex formation in the penstock and turbines of intake section [11].

Vortex is swirling flow region that rotating around an axis, either be straight or curved. Vortex generally formed during the abrupt transition from open channel flow to pressure flow. In the dam structure, vortex formation may attribute to the operation conditions and is undesirable [11-13]. As a result, the power generated by the turbine blades would be decreased and lowered the hydroelectric power generation by up to 80%. Additionally, both erosion and accretion are likely to occur and further poses threat to the reliability of dam structure and affecting the continuous operation of dam and hydroelectric power station.

To scrutinize the vortex flow in the intake section, flow visualization approach can be implemented to study the dynamic of vortex flow. Accordingly, the particle image velocimetry (PIV) was adopted to analyse the dynamic nature of vortex flow. PIV can be easily executed using transparent model and clear working fluid with seeding particles. In the past, PIV had seen various implementations in the fluid flows sectors of hydraulic engineering and electronic packaging [14-16]. Nonetheless, there is lack of PIV work being reported in the field of dam reliability analysis.

For the current study, the water flows along the penstock pipes in the intake section were numerically simulated using finite volume method (FVM) based software. As a validation analysis for the numerical model, the particle image velocimetry (PIV) experiment was conducted on a scaled-down physical model of penstock. There are seven different operating conditions being studied in the present works, to determine the locations and conditions of potential vortex formation.

2. Numerical Simulation

This section presented the numerical simulation works employed in the modelling of the penstocks flows. By using commercially available finite volume method (FVM) based software, ANSYS Fluent, the water flows in penstocks and turbines of dam bottom outlet section were numerically simulated. Figure 1 depicted the fluid domain of the bottom outlet section, with four penstock pipes that connecting the upstream intake sector to the turbine blades at the downstream powerhouse. The investigated flow is three-dimensional, unsteady, incompressible, and turbulent.

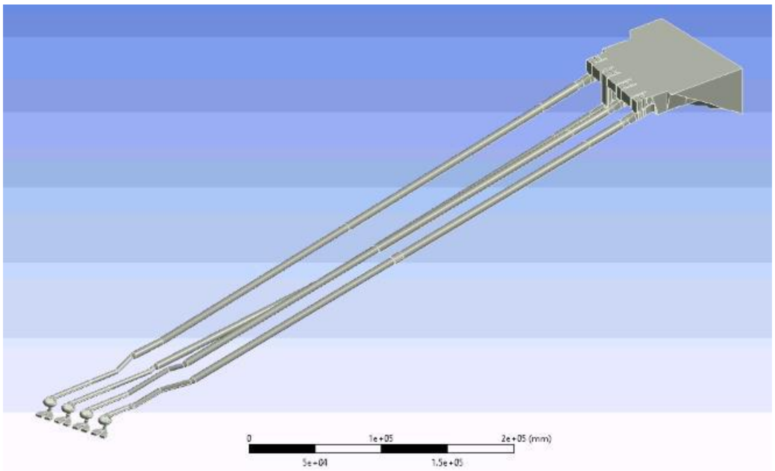


Fig. 1. Fluid domain of the investigated bottom outlet section model that comprised of four penstocks and four turbines

The governing Navier-Stokes equations were discretized based on the finite volume method (FVM) scheme and were solved numerically, for instance momentum equation and continuity equation, respectively given as follows:

$$\frac{\partial}{\partial t}(\rho\vec{\mathbf{v}}) + \nabla\cdot(\rho\vec{\mathbf{v}}\cdot\vec{\mathbf{v}}) = -\nabla p + \nabla\cdot\vec{\boldsymbol{\sigma}} + \rho\vec{\mathbf{g}} + \vec{\mathbf{F}}, \tag{1}$$

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{\mathbf{v}}) = 0, \tag{2}$$

where $\vec{\mathbf{v}}$, fluid flow velocity vector, ρ, fluid density, p, pressure, $\vec{\mathbf{g}}$, gravitational acceleration, $\vec{\boldsymbol{\sigma}}$, stress tensor, $\vec{\mathbf{F}}$, external applied force term and t, time [17,18].

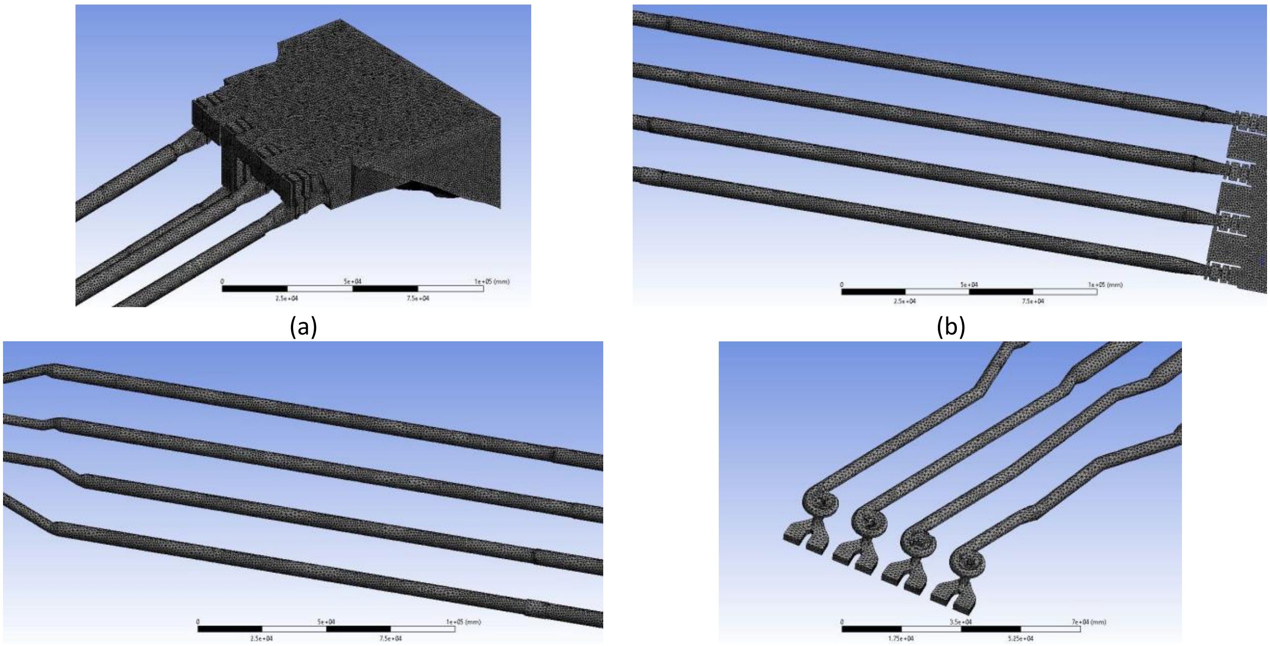
Additionally, the multiphase implicit volume of fluid (VOF) scheme was employed to track the instantaneous position of water flow front. The first phase is the air while the second phase being the water. The governing equation for VOF scheme is the transport equation, given as follows:

$$\frac{\partial f_n}{\partial t} + \vec{u}\cdot\nabla f_n = 0, \tag{3}$$

where f_n is the volume fraction of n-th phase, in which $n = 2$ for the present simulation [17,18].

The initial water level at the upstream intake section near the penstock inlets is 244.92 m and the free water surface is set as the pressure inlet. Meanwhile, the other end of penstock pipes connecting to the turbines were set as the pressure outlet of 0 Pa (gauge). Elsewhere the boundary walls of the penstock pipes were set as no-slip.

The fluid domain was meshed based on the tetrahedrons assembly meshing method, with both the proximity and curvature settings enabled. The generated meshed numerical model of the penstock pipes according to the optimized mesh settings was depicted in Figure 2. Subsequently, the numerical simulation was executed using the optimized time step of 0.01 s was selected, for a total of 1500 steps.



(a) (b) (c) (d)

Fig. 2. Meshed fluid domain based on the optimized mesh settings; (a) Intake section, (b) First part of penstocks connected to the intake, (c) Second part of penstocks connected to the turbines, (d) Turbines

3. Results and Discussions

3.1 Particle Image Velocimetry Validation

The validation analysis was conducted based on particle image velocimetry (PIV) experiment. PIV is a non-invasive optical method for the identifications of flow velocity vectors and distributions for a cross-sectional plane fluid flow [12,14]. Figure 3 and Figure 4 depicted respectively the schematic and actual PIV experiment being conducted on the scaled-down penstock model, to visualize the flow dynamics along the investigated section of penstock. To attain visibility of fluid flow, the scaled-down penstock model was constructed using clear Perspex. Filler particles were added to the working fluid as trackers, which will be illuminated by reflecting the laser illumination. Lastly, the images obtained from the PIV experiment were pre-process to have their qualities enhanced and the noises removed. The flow velocity vector distribution was obtained in the analysis stage using the PIVlab software.

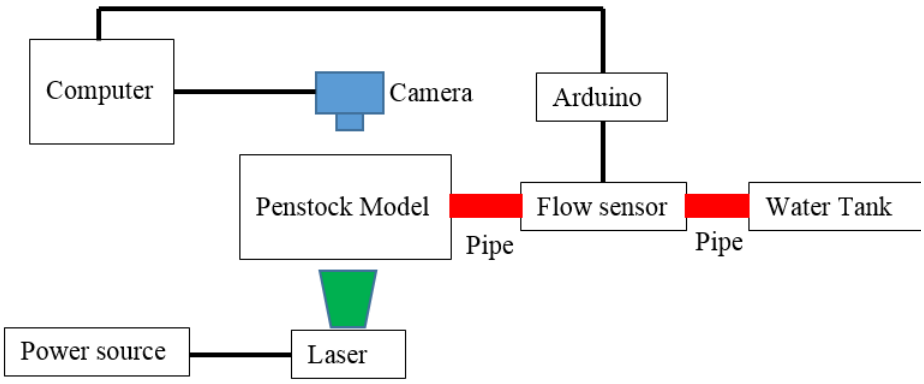


Fig. 3. Schematic of the PIV experiment

Fig. 4. Actual PIV experiment

Both numerical simulated and experimental velocity contours were qualitatively compared and shown in Figure 5. It was found that both the flow vectors are qualitatively comparable, with similar flow natures exhibited circled regions shown in Figure 5. Moreover, the discrepancy between the maximal flow velocities obtained from numerical simulation and experiment is 12%. Therefore, the veracity of the current simulation model is affirmed.

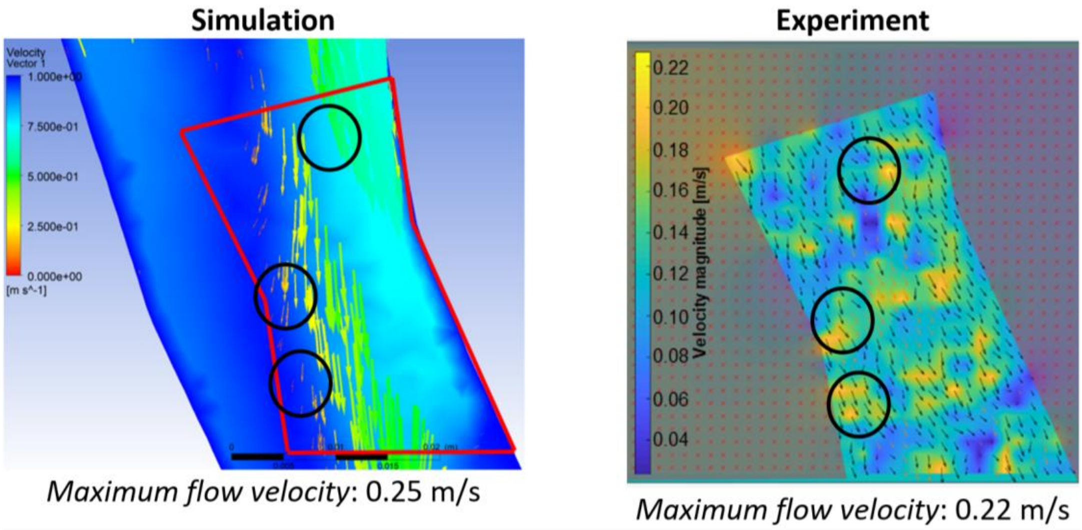


Fig. 5. Simulated and experimental flow velocity contours

3.2 Volume Fraction

Table 1 gives the volume fraction of the penstocks flows at various operating conditions. When the water level of reservoir dam is at the lowest of 244.92 m, all four penstocks are not fully filled with the water. The penstocks *A* and *C* were partially filled with water until half of the penstocks and then start to decrease until it reaches the turbine. This happens because of low water pressure when the dam reservoir at the lowest level. For the penstocks *B* and *D*, the water is almost fully filled in the penstock. There is a void occurring at the bottom section of the penstock because there is a slight change to the shape, direction, and angle of the penstock pipe.

Table 1
Volume fraction of the simulated penstocks flows for seven operating conditions

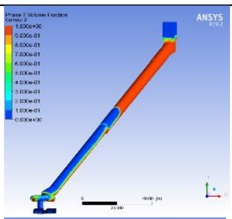
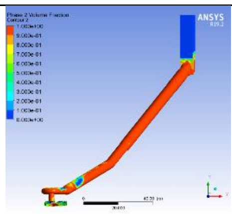
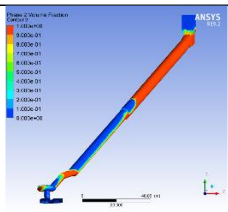
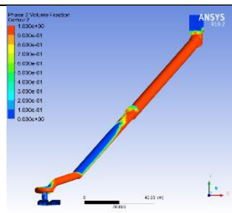
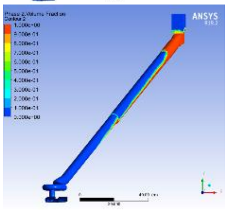
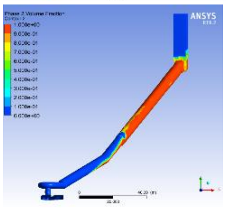
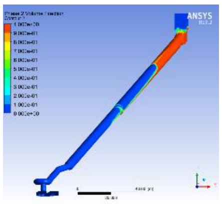
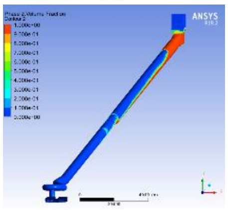
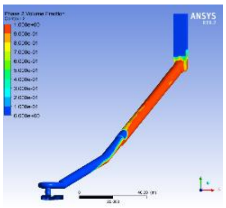
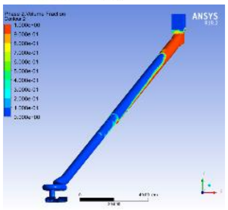
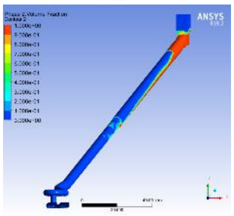
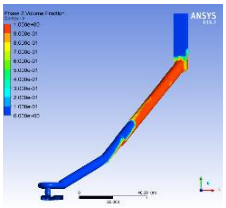
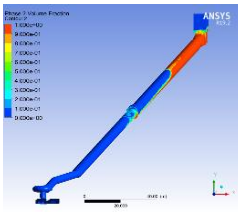
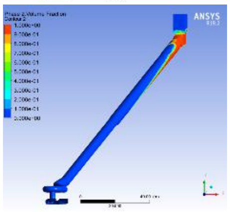
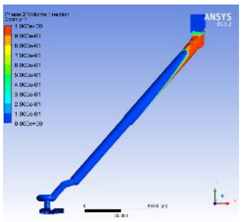
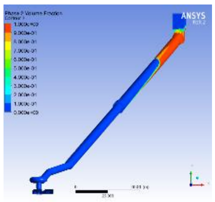
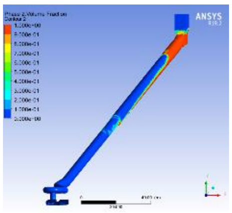
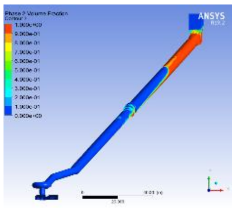
Operating conditions	Penstocks *A*	*B*	*C*	*D*
1				
2				*Closed*
3			*Closed*	*Closed*
4		*Closed*	*Closed*	*Closed*
5			*Closed*	
6		*Closed*		
7		*Closed*	*Closed*	

Figure 6 shows the positions of four investigated penstocks, *A*, *B*, *C* and *D*, in which the position of intake of penstock *B* is at the lowest. This make the distance between water surface and intake B higher than other intakes. Thus, the water pressure is high to flow water through Penstock B to downstream. This may be a major factor that contribute to the low power input generated by the station when the water reservoir is at the lowest level. For penstock *A*, *C* and *D*, the volume fraction of water is full only at the top of the penstock after the intake. For Penstock *B*, the volume fraction of water is full until the middle of the penstock. The simulation results for operation conditions 2–7 have no significant changes, meaning there are no effects when some of the penstocks close at the intake.

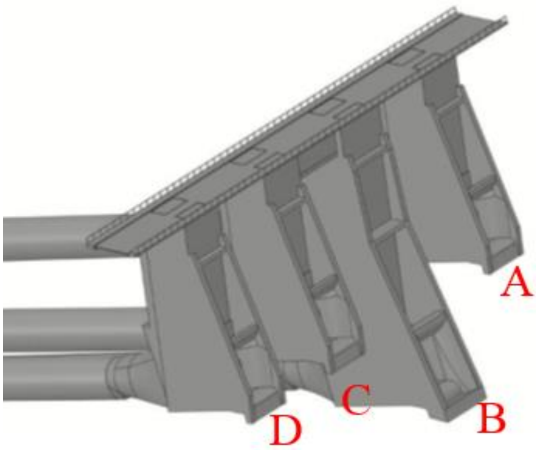


Fig. 6. Labels of the four penstocks intakes, *A*, *B*, *C* and *D* for the subsequent analyses

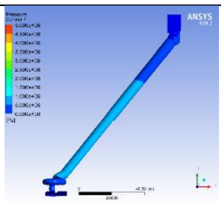
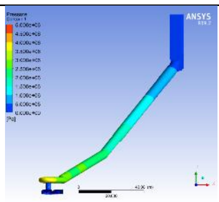
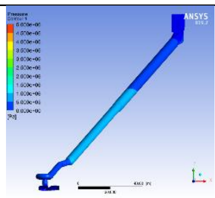
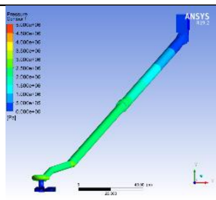
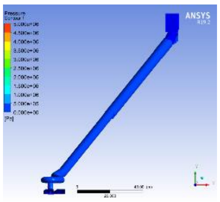
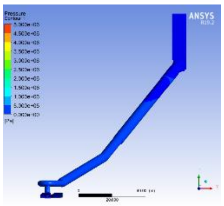
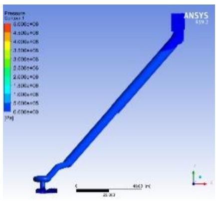
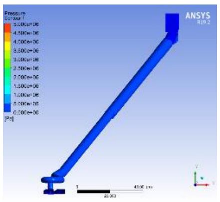
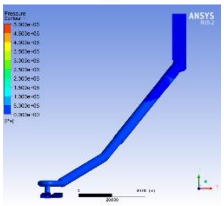
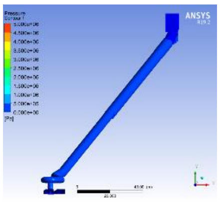
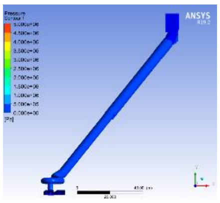
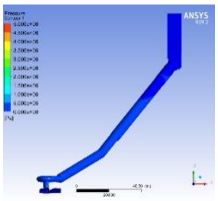
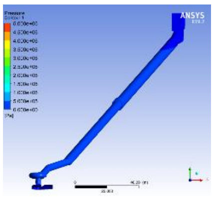
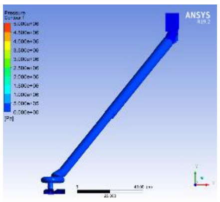
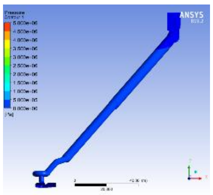
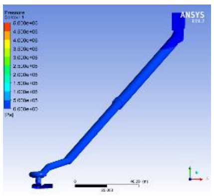
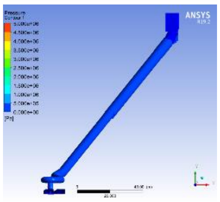
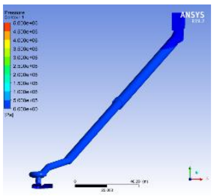
3.3 Pressure

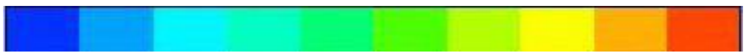
Table 2 presents the pressure contours of the water flow in all penstocks at various operation conditions. For the first operation condition in which all four penstocks were opened, the colour contours for the flow pressure gradually decreasing as the water flows toward the downstream turbines. This is in accordance to the Bernoulli's principle, which states the dynamic pressure of water is inversely proportional to the flow velocity. The flow velocity gradually increasing as it flows toward the turbines upon being accelerated by the gravity. In the penstocks *A* and *C*, the maximum pressure is 1.2 MPa. For penstock *B*, the maximum value of pressure is the highest among the four penstocks, which is 4.5 MPa. Meanwhile, for penstock *D*, the maximum value is 3.4 MPa. For the operation conditions 2–7, the maximum pressure value obtained is 0.8 MPa in all four penstocks. Generally, the water pressure increases as it approaches the downstream turbines.

3.4 Velocity

Table 3 showed the velocity vectors in the four penstocks for the operation condition 1 in which all penstocks were opened. The critical flow sections for the respective penstocks were indicated as circle. It was found that the overall flow vector in the penstocks is relatively stable except for a few regions. For the penstock *A*, at the intersect point between two parts of penstock, the flow vector is unsteady. This is caused by the sudden change of shape and flow area of the penstock pipe, giving non-uniform flow. The stepped shape altered the flow direction and causes unsteady flow. Additionally, that region was not fully filled with water. Similarly, this phenomenon also observed at the penstock *C* where there is a sudden change for the shape and area.

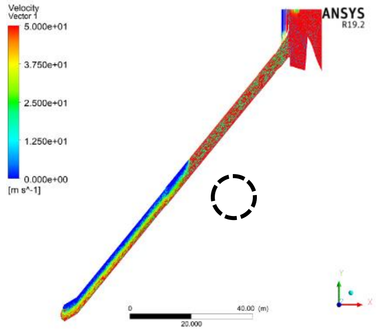
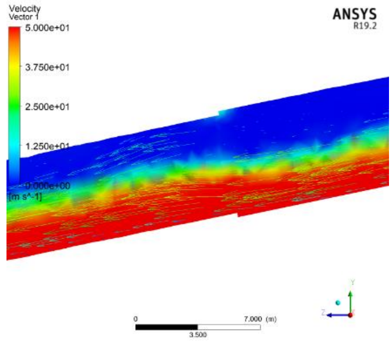
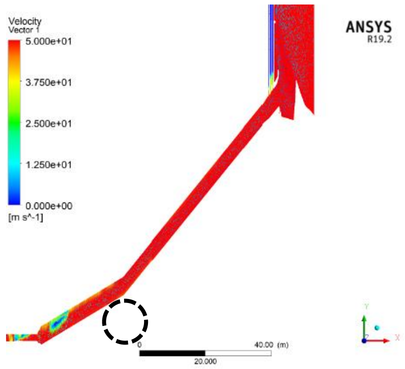
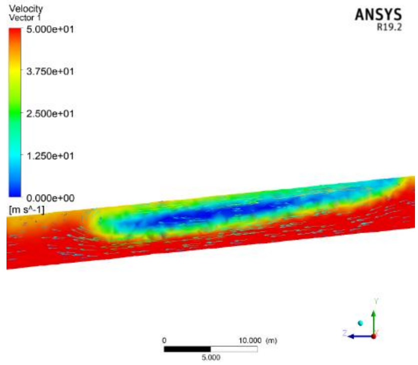
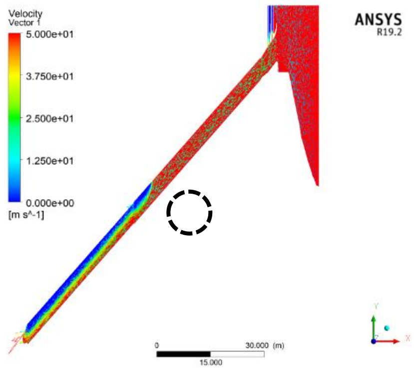
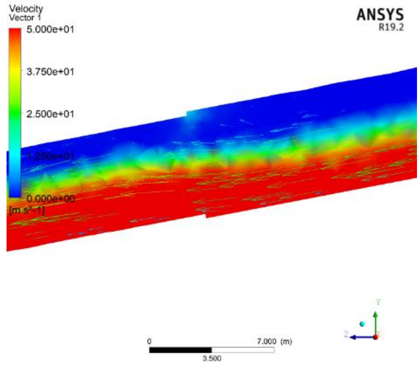
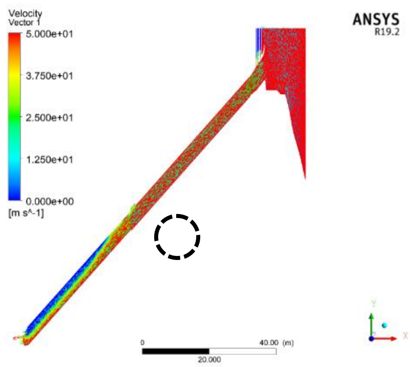
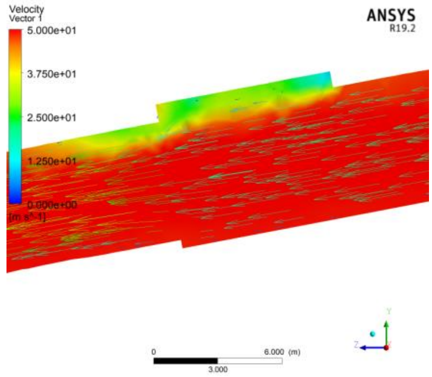
Table 2
Flow pressure in the penstocks for seven operating conditions

Operating conditions	Penstocks *A*	*B*	*C*	*D*
1				
2				*Closed*
3			*Closed*	*Closed*
4		*Closed*	*Closed*	*Closed*
5			*Closed*	
6		*Closed*		
7		*Closed*	*Closed*	



0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 (MPa)

Table 3
Velocity contours of the overall penstock flows and the flows at critical section

Penstocks	Flow velocity profile at penstock	Critical section (circled)
A		
B		
C		
D		

At the bottom section of penstock *B*, there are a void occurring at that area, which potentially inferred as the swirling flow. It can be said that the vortex formation had occurred in that region. As the water fully filled the penstock B, the velocity of water increases due to the hydrostatic pressure and this high velocity resulted the water flow to exhibits turbulence nature and prone to the swirling formation. At the penstock *D,* the vector flow is observed at the middle part where there is a sudden change in shape and area of the penstock. It founds that the flow is in uniform steady move. The volume fraction of water is full in this area compare to the regions from penstock A and C. Thus, the flow is move in steady condition.

Moreover, the swirling and vortices were detected at the flow along the penstock *B*. However, there is no significant observable vortex being formed in the penstock *A*, *C* and *D*.

4. Conclusions

In this paper, the water flows in dam intake sections along the penstocks were numerically simulated using finite volume method (FVM) based software, ANSYS Fluent. The current numerical model was validated with the particle image velocimetry (PIV) experiment. It was found that both the numerical and experimental findings were in great consensus, affirming the veracity of the mathematical models. There are seven different operating conditions being considered by separately closing selected penstocks. The low reservoir water level caused the small intake water pressure, thus the hydropower station unable to achieve full efficiency to generate power input. Moreover, there is a void occurring at the bottom section of the penstock. The maximum pressure for each penstock is found at the bottom section of the penstock approaching turbine. Nonetheless, there is no vortex formation occur in penstocks *A*, *C* and *D*, despite there is swirling being detected at penstock *B*. This study provided useful insights for future dam reliability analysis particularly on the intake section and penstocks. Furthermore, the identification of vortex and swirling in the penstock enabled the subsequent mitigation action to be taken, thus, to improve the efficiency of hydroelectric generation.

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