

Numerical Study of the Flow-Induced Vibration During Tunnel Surging at the Intake Section of Chenderoh Dam

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Abstract. Chenderoh Dam that located in Malaysia is one of renewable energy power plant that beneficial to mankind. However, in some cases, the dam suffers from the vibration effect during the water spilling from upstream to downstream. This study focused on major part of the dam which is the intake section during the tunnel surging condition. A detail 3D model of the intake section was constructed and used in the prediction of flow-induced vibration response. The results of frequency domain response and operational deflection shapes (ODS) from the effect of flow-induced vibration are compared with the natural frequencies and mode shapes of the dam. From the results, the transient vibration responses due to the flow of water occurred at the frequency of 8.63 Hz with the maximum deformation of 8.24×10^{-1} m, meanwhile, the modal analysis obtained at 2.76 Hz of natural frequency with deformation of 9.1×10^{-4} m. The deformation of ODS is high because of the water flow and tunnel surging condition. However, there is no resonance phenomenon occurred, yet a safety precaution must still be considered by the operator based on this result.

1. Introduction

A major interest in dam study is the prediction using fluid-structure interaction (FSI) which based on the finite volume method (FVM). Both interactions can be described as stable or oscillatory, between the structure and surrounded fluid-flow. To date, many researchers used this approach as prediction in determining the flow-induced vibration studies. For examples, the studies on the effect of radial gate [1,2], sliding gate [3] and double curvature arch dam [4] to the dam structure and water flow have been conducted. Another study on the effect of reservoir water level fluctuation to the non-linear seismic behavior of high concrete dam also has been done [5].

Vibration study on the dam structure offers different prospective learning, whereas a safety measure can be taken where its considering people life. Generally, the vibration caused by the fluid-flow is a major factor in degradation and failure of the dam structure. For example, there is a study focused in finding an optimal control of valve for the dam operation. This study suggested that valves with rounded edges and a sloping bottom has lower deflection amplitude which can reduced the vibration force and

less possibility to damage the dam wall [3]. Fei Chong et. al. studied the effect of different radial gate height with force exerted to the wall during water flow. The findings show that, the 8 m gate height exerted lower force which can reduced the vibration effect [2]. Another significant finding on vibration induced by fluid is it can lead to the catastrophic failure if natural frequencies coincide with shedding frequencies of the flow. A good dam structure will have different trend of frequency response function (FRF) from the shedding vibration [6].

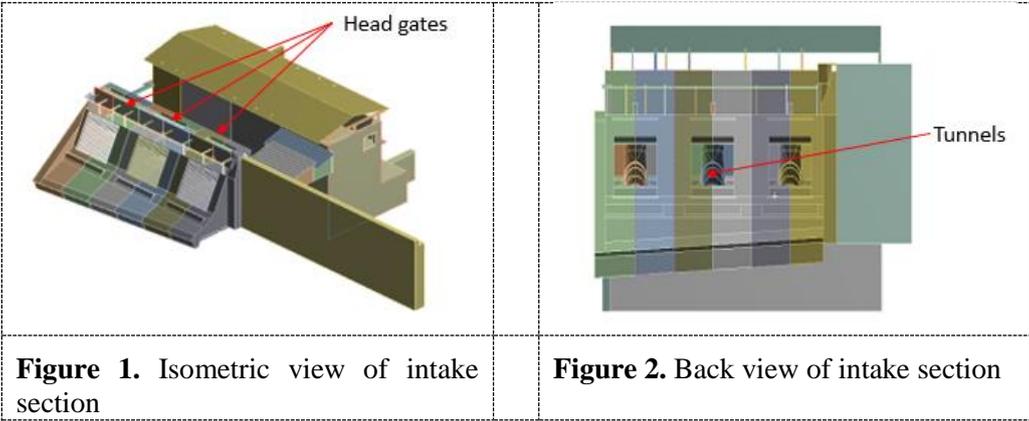
Operating deflection shape (ODS) is introduced to get full-field dynamic response of the structure. This method can described the vibration pattern of any structure with influence by its known or unknown operating frequencies [7]. Some suggested that, ODS provides more reliable dynamic information than a mode shape since it can be produced at any single harmonic frequency and not restricted to the natural frequencies [8]. This is the main reason why ODS has been applied in variety damage identification such as in polymeric composite plates [9] and beam with different types of damage (i.e. surface slot, surface holes and fatigue cracks) [10].

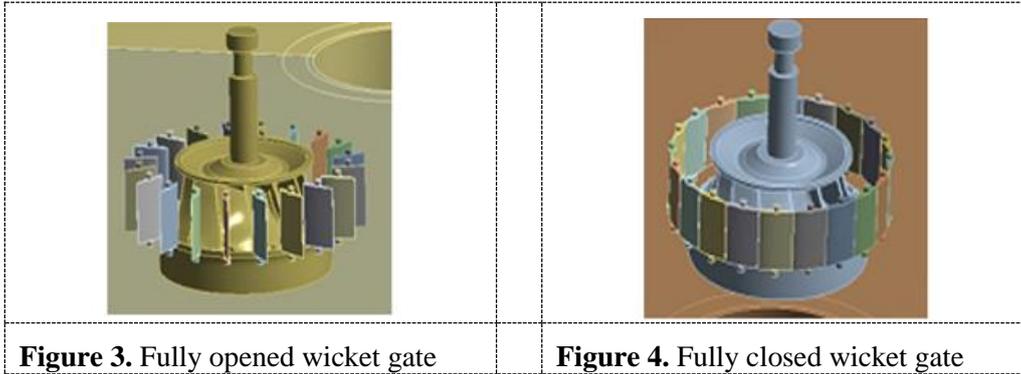
Chenderoh Dam is an oldest dam in Perak region that located in Malaysia. None of numerical study has been conducted to study the vibration that related to the dam structure. Based on literatures, the finite element method (FEM) and FVM were chosen to predict the vibration characteristic specifically in crucial part which is intake section where the electricity is generated. The study will compare with ODS and modal analysis (MA) results to determine the deformation occurred and relate it with resonance phenomenon for the safety concern of the dam structure.

2. Methodology

2.1. Modelling and Boundary Condition

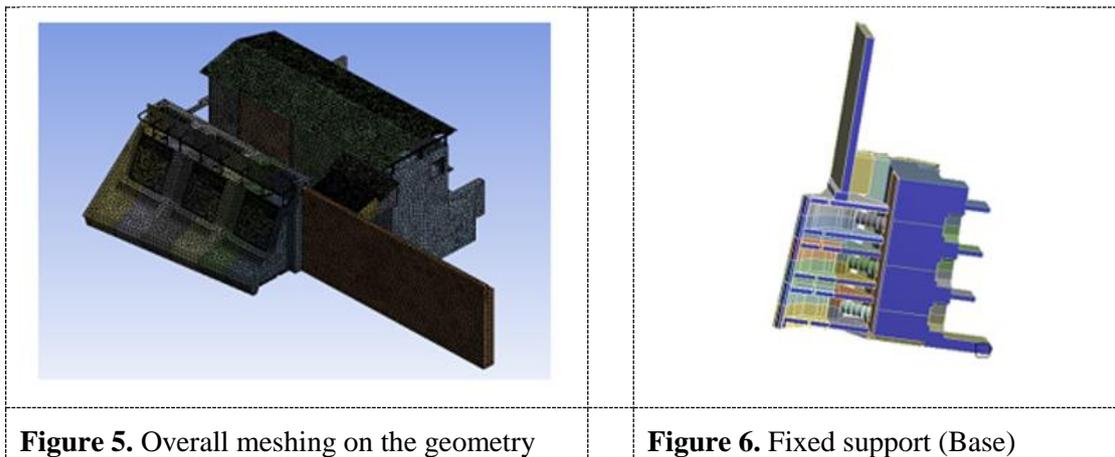
Intake section consists of three head gates, turbines and wicket gates. In this study, the case of head gates fully opened and wicket gate fully closed will be conducted as shown in Figure 1-4. So, the water will flow from upstream to downstream with maximum velocity and stopped by the wicket gates. The study only focused on the water surging effect when the wicket gates are closing inside the pen stock and the effect of the flow-induced vibration to the intake section. The real scale 3D model of intake section is constructed using SolidWorks software as shown in Figure 1 and 2.





2.2. Modal Analysis (MA)

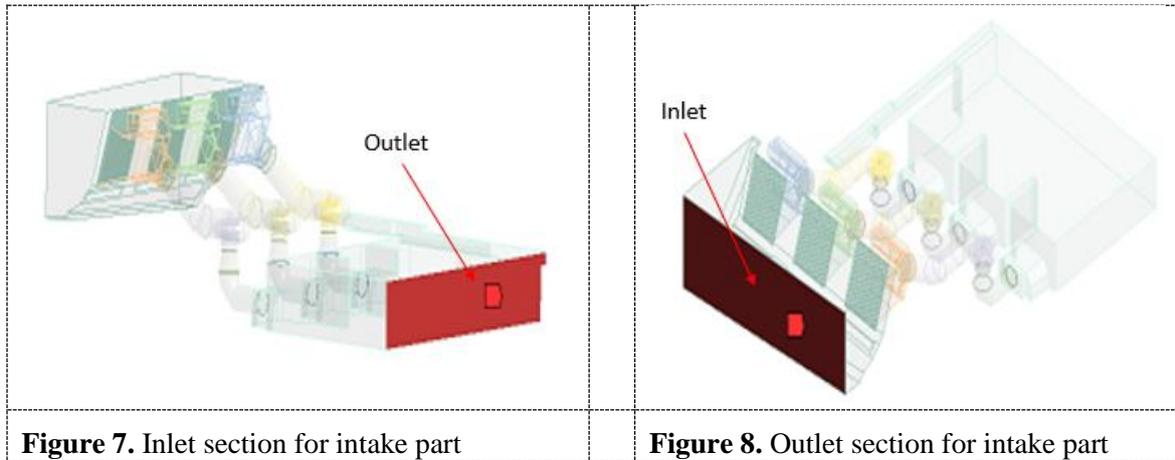
This analysis is conducted to determine the vibration characteristic such as resonant frequencies and mode shape [11]. Each part (i.e. penstock, wall and piping) were applied with its real material properties (i.e. concrete, steel and zinc) from the engineering data. The geometry is meshed with tetrahedra element for better accuracy [12]. Figure 5 shows meshes that represented the physical domains of the geometry. After that, the base (blue faces) of the structure is set as fixed support to represent the foundation and restrict its degree of freedom as shown in Figure 6.



Then, the modal analysis is performed to determine the dynamic properties at certain range of frequency called FRF. The dynamic properties can be simulated in terms of deformation, velocity or acceleration [13]. In the analysis setting, the gravity force with magnitude of 9.81 ms^{-1} is applied to all three directions. The solution method used is mode superposition interval and set to 50 natural frequencies and mode shapes.

2.3. Fluid Structure Interaction (FSI)

This analysis is used to determine the interaction of the dam structure with fluid region from upstream to downstream. The type of mesh and boundary condition used is the same as in MA. In the analysis setting, the time step end is set to 5 seconds and maximum-minimum sub-step are set to 1 and 100 respectively. The earth gravitational acceleration is applied to negative y-direction with magnitude of 9.81 ms^{-1} . In the initial fluent setting, the fluid is modelled as 3D incompressible flow and the water-air is modelled using implicit VOF. Figure 7 and 8 shows the setting of inlet and outlet for the intake section, respectively. The intake part is supplied with water velocity of 1 ms^{-1} . For the interaction of fluid and structure, the system coupling is executed to analyse both data transfers. In this system, the end time is set to transient structural system which is 5 seconds and vice versa for time step size.



The deformation data obtained from FSI analysis is then converted to frequency domain data through the fast Fourier transform (FFT) equation. After that, the FFT and FRF graph are observed and compared.

3. Results and Discussion

3.1. ODS Results of Intake Section

Figure 9(a) shows the ODS of the intake section in time range of 5 seconds. The maximum displacement occurred at trash rack with overall displacement of 8.24×10^{-1} m (average). In time domain, the deformation is likely to decay along time as shown in Figure 9(b). At $0 < t < 1$, the water surging from upstream to downstream cause the transient deformation at the intake structure. For $t > 1$, the water flow reached steady-state and deformation decrease along the time.

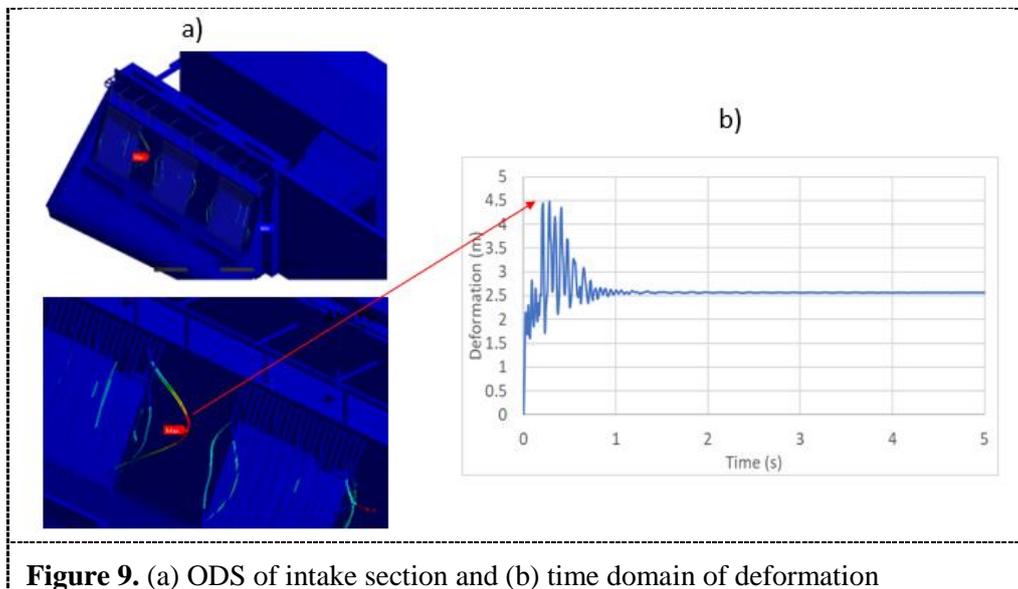


Figure 9. (a) ODS of intake section and (b) time domain of deformation

3.2. Comparison between MA and ODS

Figure 10 and 11 show the deformation occurred in the intake section from the MA and ODS results. The highest deformation found at the trash rack location with the deformation value of 8.24×10^{-1} m. This indicate that this area more likely to fail due to high velocity of water and sudden closing of the wicket gate. Differently for the MA result, the deformation occurred at rooftop with an amplitude of

$9.1 \times 10^{-4} m$. For operating and natural frequencies, it was induced at 1.18 Hz and 2.76 Hz, respectively. In overall, the transient vibration effect with operating frequency of 1.18 Hz is not coincides with the natural frequency of MA at 2.67 Hz, thus there will be no resonance phenomenon for this case. The first peak of ODS occurred due to the first impact of water spilling with wicket gate that close suddenly. Afterwards, the deformation tends to reduce based on the residue of the first transient effect of the surging. The trend for ODS is likely diverge with modal analysis. Unfortunately, due to water surging effect, the deformation is high and may cause damage the to the structure especially on trash rack. A safety concern should be considered as precaution where the wicket gate should be close properly to prevent any damage on trash rack part.

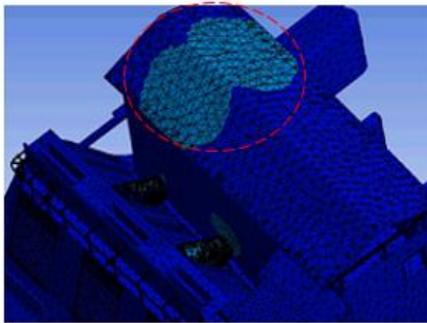


Figure 10. The deformation prediction using MA

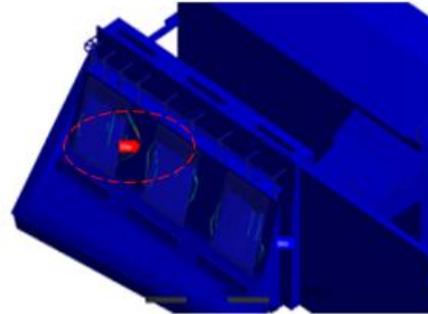


Figure 11. The deformation prediction using ODS

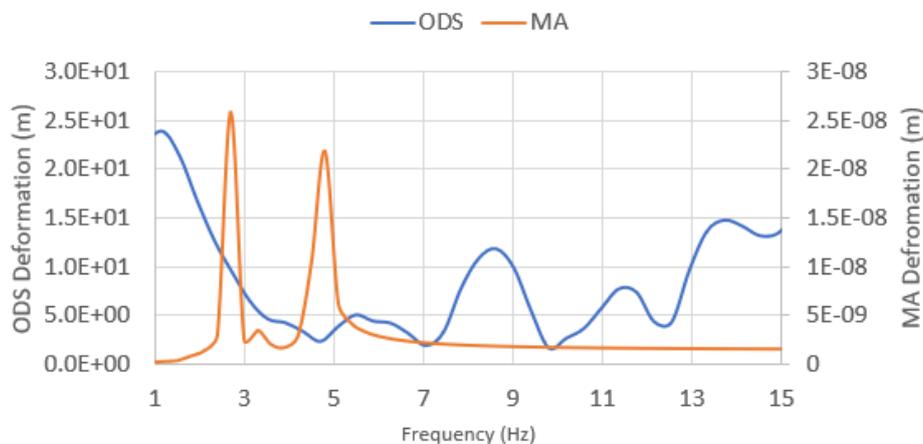


Figure 12. Comparison between MA and ODS deformation in frequency domain

4. Conclusion

Based on this study, the foresight of the vibration response at the intake section of the Chenderoh Dam can be concluded as follows:

1. A numerical method was introduced in this study to model and simulate the real scale of intake section of the Chenderoh Dam. Using the transient structural, fluent and system coupling in ANSYS, the two-way FSI has been completed in 5 second of time.
2. From ODS results, the highest deflection occurred at trash rack with operating frequency of 1.18 Hz and induced displacement of $8.24 \times 10^{-1} m$.
3. Differently for the MA, the highest deflection occurred at rooftop with natural frequency of 2.6 Hz and exhibit displacement only $9.1 \times 10^{-4} m$.

4. For comparison of both results, the trend is diverged to each other in term of frequencies and patterns. However, the deformation occurred in transient analysis (ODS) is high, so precaution steps should be taken to prevent any damage to the dam structure.

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