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Flow-Induced Vibration Response of the Chenderoh Dam Bottom Outlet Section Due to the Effects of Water Spilling

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Abstract. Hydropower-type dam can generate an electricity to the surrounding areas during the release of water from the upstream to the downstream. However, in some cases, the flow-induced vibration during the water spilling might induced significant vibration effects to the dam structure. This is a common phenomenon that happened in any of dam structures during the operating condition. In this study, the flow-induced vibration response at the bottom outlet section of the real scale Malaysian Chenderoh Dam model is investigated using ANSYS software. The results of frequency domain response and operational deflection shapes (ODS) from the flow-induced vibration are compared with the natural frequencies and mode shapes of the bottom outlet section. From the study, the transient vibration responses induced from the flow of water occurred at the operating frequency of 23.14 Hz while the natural frequency of the bottom outlet section is located at 9 Hz of frequency. This indicates that for the normal case of water spilling at the bottom outlet section, there is no resonance phenomenon happened. However, this result is useful for the dam operation section in order to avoid any disaster of the dam structure in the future.

1. Introduction

The vibration induced from the flow of water to the dam structure can lead to catastrophic failure if its natural frequencies coincide with the shedding frequencies of the flow due to the resonance phenomenon [1, 2]. The force values induced by the water depends on the pressure and velocity of the flow as well as the material properties of the actual structure. Studies regarding the flow-induced vibration on various samples have been conducted over the years but only few involved the dam structures.

The studies on the radial gate that based on its opening were conducted by Salazar [3] and Lee [4]. Simulations for both studies were performed using ANSYS software. Based on the simulation results from Salazar, the flow does not directly induced vibration on the gate but rather on the spillway structure. Lee also found that maximum acceleration occurred at gate opening height of 0.08 m. Another study was conducted by Ilgar *et al.* [5] to investigate the dynamic behaviour of the gate for different shape of valves.

Fluid-structure interaction (FSI) analysis can be applied using both monolithic or partitioned methods. Partitoned method can be further broken down into one-way and two-way FSI [6]. Comparison study between monolithic and partitioned approaches have been conducted over the years and information regarding both methods can be found in literature [7]. For one-way and two-way FSI, Ezkurra *et al*. [8] and Benra *et al.* [9] have studied both methods and they found that two-way FSI gives more reliable results.

Generally, there are two conditions of water flow phenomenon in Chenderoh dam; water spilling and surging. Water spilling occurs when all the gates are fully opened, and maximum amount of water is released from upstream to downstream area. For the water surging, all the gates are suddenly closed during emergency. In this paper, the water spilling case is studied where the bottom outlet section is modelled exactly as the original drawing of the Chenderoh dam. The FEM model used the properties of the real concrete materials and two-way FSI simulation study is performed using ANSYS transient structural and fluent workbenches and the results are compared with the modal and harmonic analyses.

2. Methodology

2.1. Modelling of the bottom outlet section of the dam structure

The three-dimensional (3D) model of the bottom outlet section is constructed using SolidWorks software, as shown in Figure 1. Bottom outlet section is the second source of power generation for the Chenderoh dam and it has the underground penstock for the release of water from upstream to downstream area. The release of water is controlled by two butterfly gates, as shown in Figure 2.

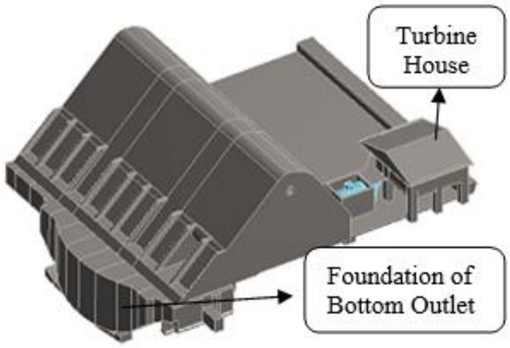

Figure 1. 3D model of the bottom outlet section of Chenderoh dam.

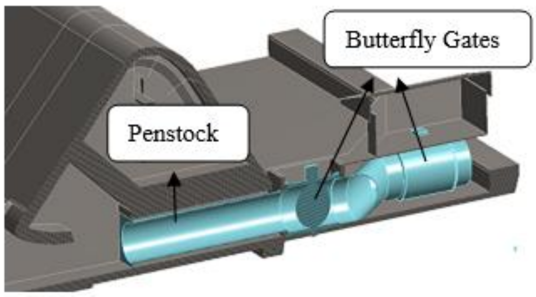

Figure 2. Locations of the butterfly gates of the bottom outlet section.

2.2. Boundary conditions of the structure and fluid of the dam

For the bottom outlet structure modelling in the ANSYS Transient, the boundary condition that been set for all the bottom faces are fixed support, as shown in Figure 3.

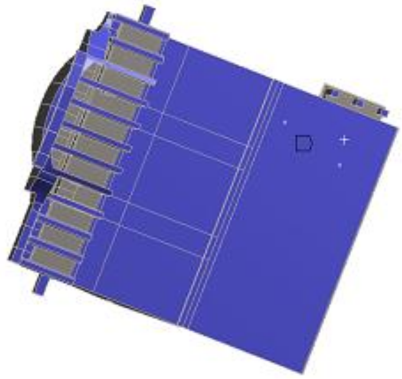

Figure 3. Boundary condition of the bottom outlet section.

For fluid section in ANSYS Fluent, the type of boundary conditions for inlet and outlet sections are

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velocity inlet and pressure outlet, respectively. The inlet velocity magnitude for water is set as 1 m/s. Figure 4 and 5 show the inlet and outlet areas of the bottom outlet section respectively.

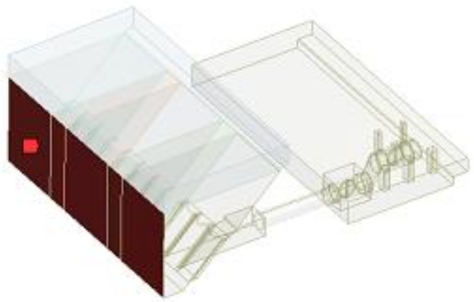

Figure 4. Inlet area for the fluid domain of bottom outlet section.

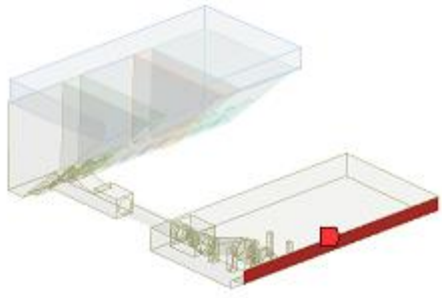

Figure 5. Outlet area for the fluid domain of bottom outlet section.

2.3. Two-way fluid-structure interaction (FSI) of the bottom outlet section

Two-way FSI of the bottom outlet section is made up of two systems analyses (Transient Structural and Fluent) and one integrated system (System Coupling) located in the ANSYS software. These systems are linked together as shown in Figure 6. Compared to one-way method, the displacement of the structure is also transferred to the fluid solver in two-way FSI [10]. Although it has higher computational cost than one-way FSI, it can produce more accurate and stable results [11].

For the Transient Structural system, the type of mesh used is tetrahedral mesh. In the analysis of bottom outlet section, the step end time is set to 5 seconds and the step control is defined by substeps. After setting-up the boundary condition as shown in Figure 3, the standard earth gravity acceleration of 9.8 m/s^2 is applied at *–y* direction. In the Fluent system, an automatic mesh is applied in order to reduce the simulation costs in terms of time and number of elements.

A 2nd order upwind is selected for the solution method of turbulent kinetic energy and dissipation rate. 0.01 second is set as a time step size with maximum iteration of 20 times. In the System Coupling (integrated system), the end time is set similar to Transient Structural system which is 5 seconds and the time step size used is 0.01 second, similar to Fluent system.

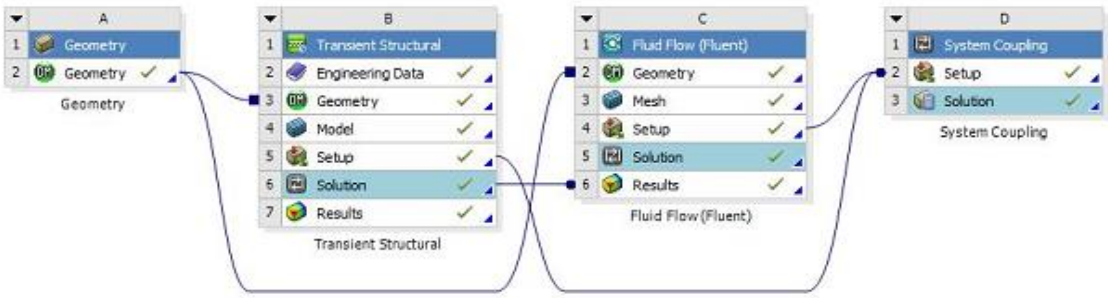

Figure 6. Linked setup between systems in two-way FSI.

3. Results and discussions

3.1. ODS results of the bottom outlet section

Figure 7 shows the ODS result of the Chenderoh dam bottom outlet section. From the figure, the deflection is mainly occurred at the upper region of the structure and there is no significant effect at the penstock and turbine house locations caused by the water flown.

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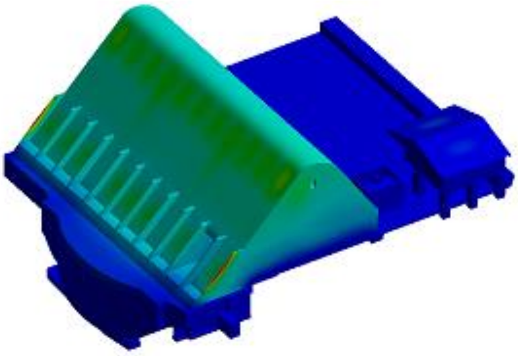


Figure 7. ODS of the bottom outlet section.

It can also be observed in Figure 8 and 9, the ODS results of the bottom outlet section in terms of time and frequency domains. From the frequency domain graph, the highest overall deflection occurs at the operating frequency of 23.14 Hz with maximum displacement value of 5.36 x 10^{-1} m.

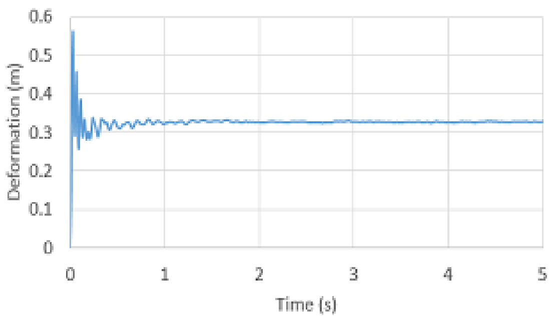


Figure 8. Time-domain graph of the deformation of the bottom outlet section.

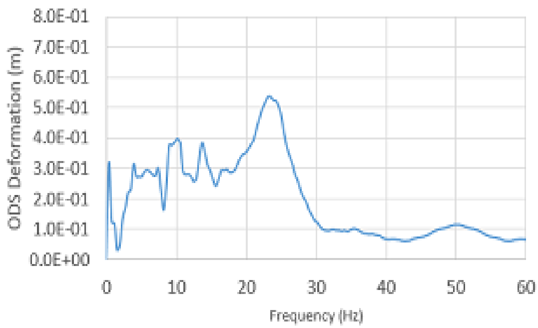
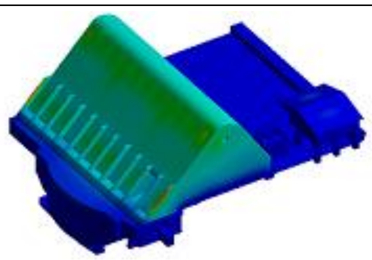
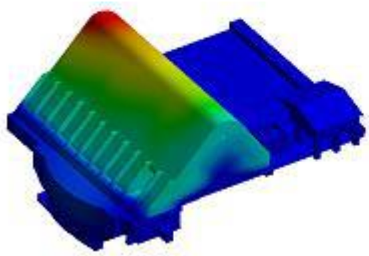


Figure 9. Frequency-domain graph of the deformation of the bottom outlet section.

3.2. Comparison between ODS and modal analysis (MA) of the bottom outlet section

Table 1 shows the ODS result from the Transient Analysis (FSI) and mode shape result from the Modal Analysis (MA) respectively. It can be observed that the ODS and the mode shape exhibit almost similar result where the deformation occurred at the upper region of the bottom outlet structure.

Table 1. Comparison between ODS and mode shape for bottom outlet section.

ODS	Mode Shape
	

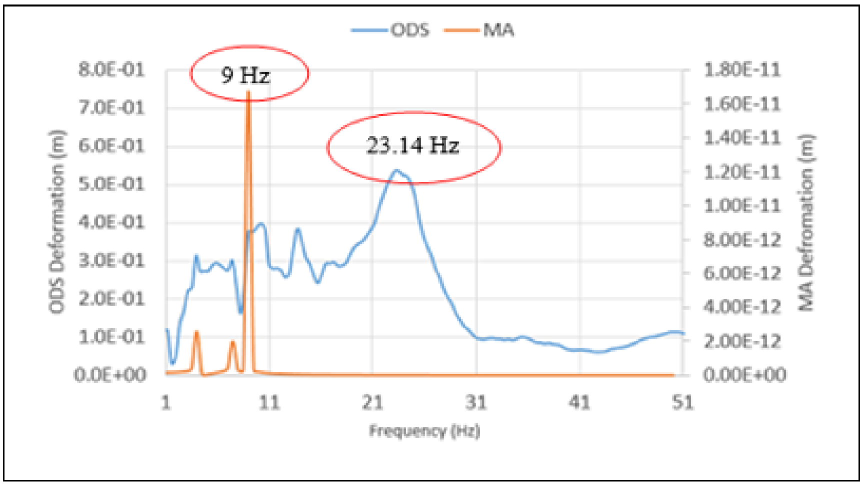


Figure 10. Relationship between ODS and MA deformations at the bottom outlet section in frequency domain.

Figure 10 shows the frequency response from the ODS and MA results. From the figure, the ODS deformation occurred at the operating frequency of 23.14 Hz and MA deformation occurs at natural frequency of 9 Hz. This means that both are in the different frequency peaks. Based on the frequency response function (FRF) of the harmonic response analysis, the highest deflection occurs in *z*-direction with amplitude value of 1.68 x 10^{-11} m. Due to the fact that these two frequencies do not coincided, resonance phenomenon did not happen. Thus, there is no significant failure can be expected at the bottom outlet section of Chenderoh dam for the normal water spilling condition.

4. Conclusion

In this study, the effect of flow-induced vibration on the Chenderoh dam bottom outlet section was successfully analysed by two-way FSI and MA using ANSYS. Based on the ODS result, the highest overall deflection occurs at the operating frequency of 23.14 Hz whereas MA deformation occurs at 9 Hz. Since both deformations occur at different frequencies, it can be concluded that there is no critical failure to the bottom outlet section because of the absence of resonance phenomenon. Similar analysis on the sections that involve the turbines or gates are still a challenge due to the complex dynamic mesh. For the future research, the effect of tunnel surging (gates are fully closed) on the bottom outlet section can be analysed.

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