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Cite as: AIP Conference Proceedings **2129**, 020043 (2019); https://doi.org/10.1063/1.5118051
Published Online: 30 July 2019

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Effect of Free Surface Water Level of Kenyir Dam on Spillway Structure using Fluid-Structure Interaction (FSI) Analysis

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Abstract. This paper investigated the effect of free surface water level of Kenyir Dam towards the stress and deformation of spillway structure by using fluid-structure interaction (FSI) simulation. The water flow across the spillway is visualized as modelled based on volume of fluid (VOF) scheme. For free surface water level of 155 m, higher stress is computed at the spillway (40.4 MPa) and at the downstream (8.9 MPa) compared to the result of free surface water level of 146 m. It is found that the higher the free surface water level caused high force exerted by the water flow on the spillway structure.

INTRODUCTION

Dams are man-made hydraulic structures that provide domestic and economic benefits such as for water storage and electricity. However, the reservoir level will increase during major rainfall events and can cause a risk of dam overtopping [1]. The spillway system is designed to spill upstream water in a safe manner to avoid the occurrence of flooding. The spillway itself includes a crest, a chute and steps on the chute that act as energy dissipator to dissipate the flow from critical to subcritical conditions before it re-joins the natural stream.

Several researches have been conducted on the flow and reliability of the dam. Potential flow theory and mapping into the complex potential plane were analysed by Cassidy [2]. Olsen and Kjellesvig [3] simulated numerically the flow over a spillway in 2-D and 3-D for various geometry and the numerical simulations of water flow over stepped spillway with different step configurations were presented by H. Chanson et al. [4]. To date, with the use of high-performance computing, computational fluid dynamics (CFD) is feasible to study the hydraulic behavior of full-scale spillways [5]. The Fluid-Structure Interaction (FSI) simulation has proven to be more reliable as it is capable to capture both aspects of fluid flow and structural deformation in the modelling [6, 7].

The objective of the paper is to conduct FSI simulations and to study the effect of free surface water level of Kenyir Dam towards the stress and deformation of the spillway structure.

5th International Conference on Green Design and Manufacture (IConGDM 2019)
AIP Conf. Proc. 2129, 020043-1–020043-7; https://doi.org/10.1063/1.5118051
Published by AIP Publishing. 978-0-7354-1871-4/$30.00

METHODOLOGY

Figure 1 shows the constructed real spillway model and its corresponding fluid domain after meshing step. The dimensions of the fluid domain are 954 m (length) x 245 m (width) x 178 m (height). Tetrahedral mesh with their mesh elements being optimized were adopted in the present simulation. Such optimized mesh enables both low computational cost at reasonably good numerical accuracy to be achieved.

The water flow across the spillway is visualized by using the Volume of Fluid (VOF) scheme. The general boundary conditions (BC) used in the current simulation is open channel with free surface level. Figure 2 shows the free surface level in the current simulation. For the mixture phase of the inlet, the total height and free surface level are used to define the velocity of the flow. Moreover, the pressure at the inlet and outlet are set to be equal to atmospheric pressure. The free surface equation as below;

$$y_{total} = y_{free} + \frac{v^2}{2g} \tag{1.1}$$

where y_{total} is total height, y_{free} is free surface level, v is velocity and g is gravity.

For hydraulic applications, the governing equations describing the behaviour of incompressible water (constant density, ρ) are the conservation of mass (continuity equation) and momentum (Navier-Stokes equation).

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1.2}$$

Navier-Stokes equation:

$$\frac{1}{\rho}\frac{\partial p_d}{\partial x} = -\frac{Du}{Dt} + \mu\nabla^2 u \tag{1.3}$$

$$\frac{1}{\rho}\frac{\partial p_d}{\partial y} = -\frac{Du}{Dt} + \mu\nabla^2 u \tag{1.4}$$

$$\frac{1}{\rho}\frac{\partial p_d}{\partial z} = -\frac{Du}{Dt} + \mu\nabla^2 u \tag{1.5}$$

Where $p_d = p + \rho g h$, a constant hydrostatic condition due to gravity, g; ∇^2 is the Laplace operator; and

$$\frac{Du}{Dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} \tag{1.6}$$

These partial differential equations, inherently nonlinear, are discretised both in space and time, and they can be solved using a variety of numerical schemes. Due to the complex nature of turbulence, it is often simplified and approximated using an averaged approach (eg. Reynolds-averaged Navier-Stoke). For practical purposes, the Re-Normalised Group k-ε turbulent energy dissipation equation has been rather successful for spillway modelling. In solving these equations, the main variables the analysis computes are velocity (a vector quantity), fluid fraction, pressure and temperature (scalar quantities) throughout the domain as a function of time for the given initial and boundary conditions.

System Coupling module were used to couple both Transient Structural and Fluid Flow (FLUENT). Such coupling procedure allows two-way data transfers between the structural region and the fluid phase. Data transfer is defined between the fluid solid interface (FSI) of the Transient Structural and contact surface in Fluid Flow (FLUENT). The time step size used in the current simulation is set at 0.01 s and the end time is 40 s. These setting will be made consistent to the similar input provided in Transient Structural. Finally, the coupled analysis is executed to solve the coupling of both structural and fluid domains.

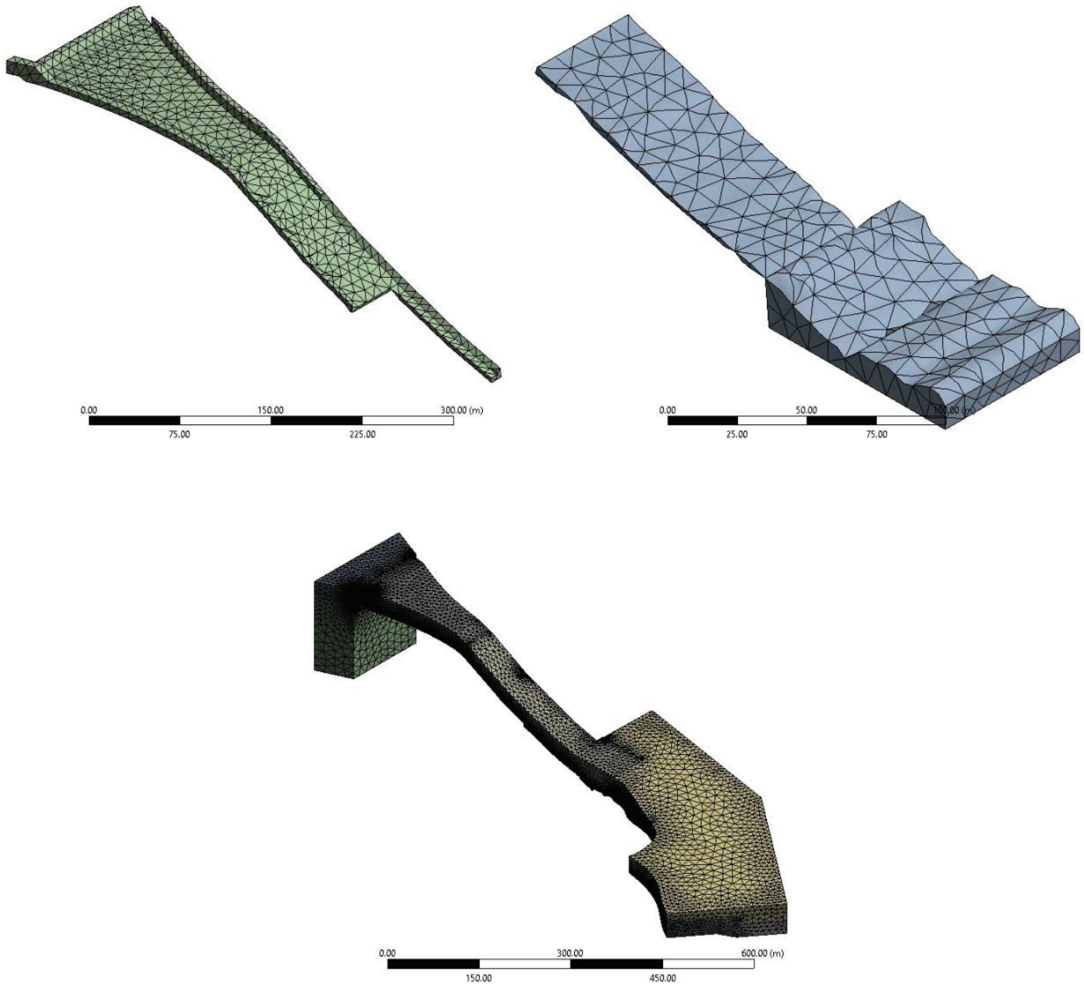

FIGURE 1. Meshed spillway domain (top left), downstream domain (top right) and fluid domain (bottom).

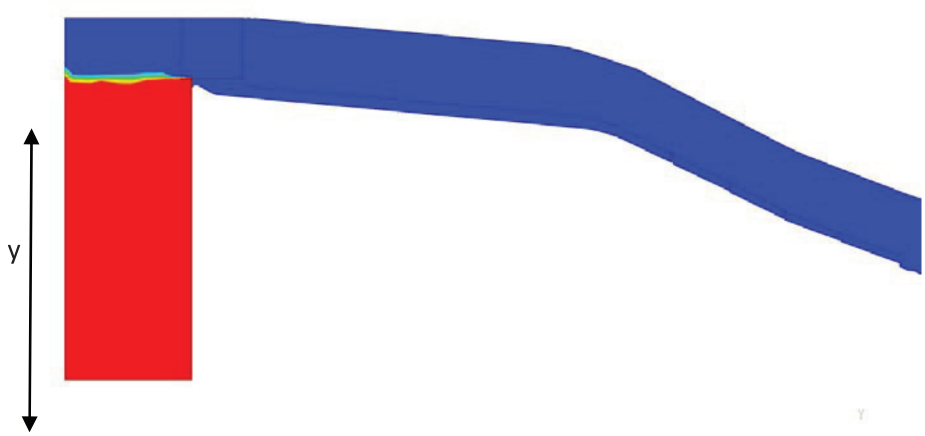

FIGURE 2. Free surface level of the spillway.

RESULTS AND DISCUSSIONS

Figure 3 shows the free surface level water of the spillway set at (a) 146 m and (b) 155 m. These free surface water levels were set based on the recent rainfall events and the worst-case upstream water level that occurred at the spillway.

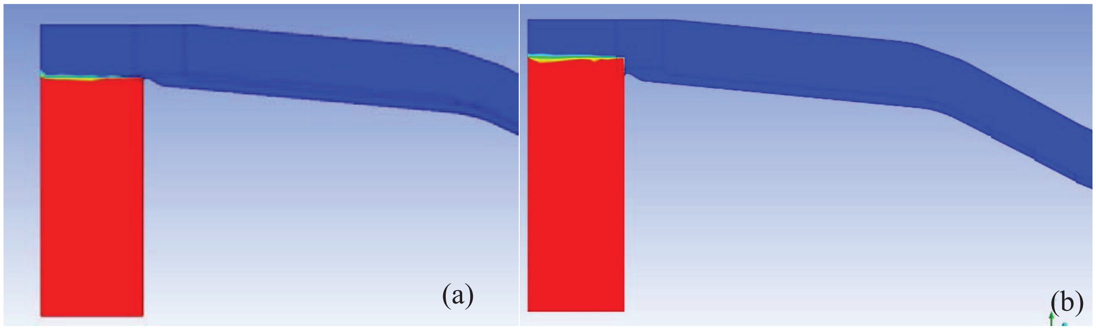

FIGURE 3. Free surface water level of spillway for (a) 146 m and (b) 155 m.

TABLE 1. Maximum stress and deformation of the spillway structure.

Free surface water level (m)	Spillway		Downstream	
	Max stress (MPa)	Max deformation (m)	Max stress (MPa)	Max deformation (m)
146	10.97	0.1	1.4	0.0003
155	40.4	0.5	8.9	0.092

Figure 4 and 5 display the stress and deformation profile on the spillway and downstream after the flow of water in 40s. The profile of stress and deformation on the structures are displayed too. The red colour shows the maximum value while the blue colour shows the minimum value. Table 1 shows the extracted max stress and max deformation data from Figure 4 and 5.

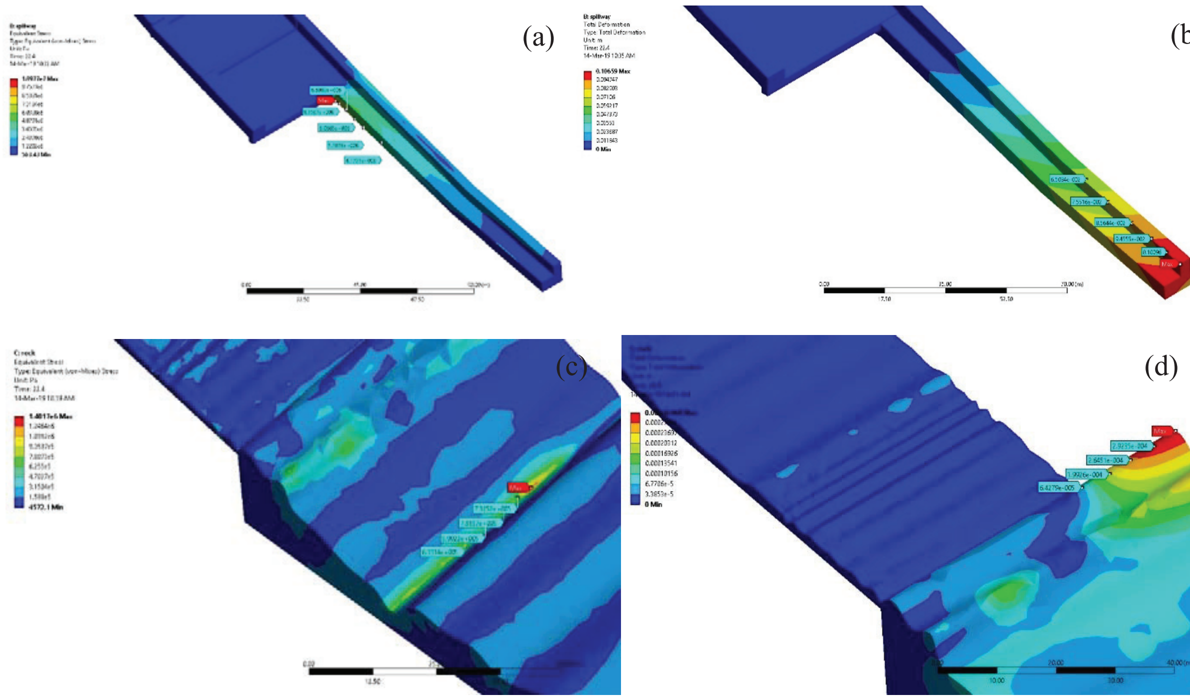

FIGURE 4. The distribution stress and deformation of the structure spillway for free surface water level of 146 m. (a) Stress of spillway, (b) Deformation of spillway, (c) Stress of downstream and (d) Deformation of downstream.

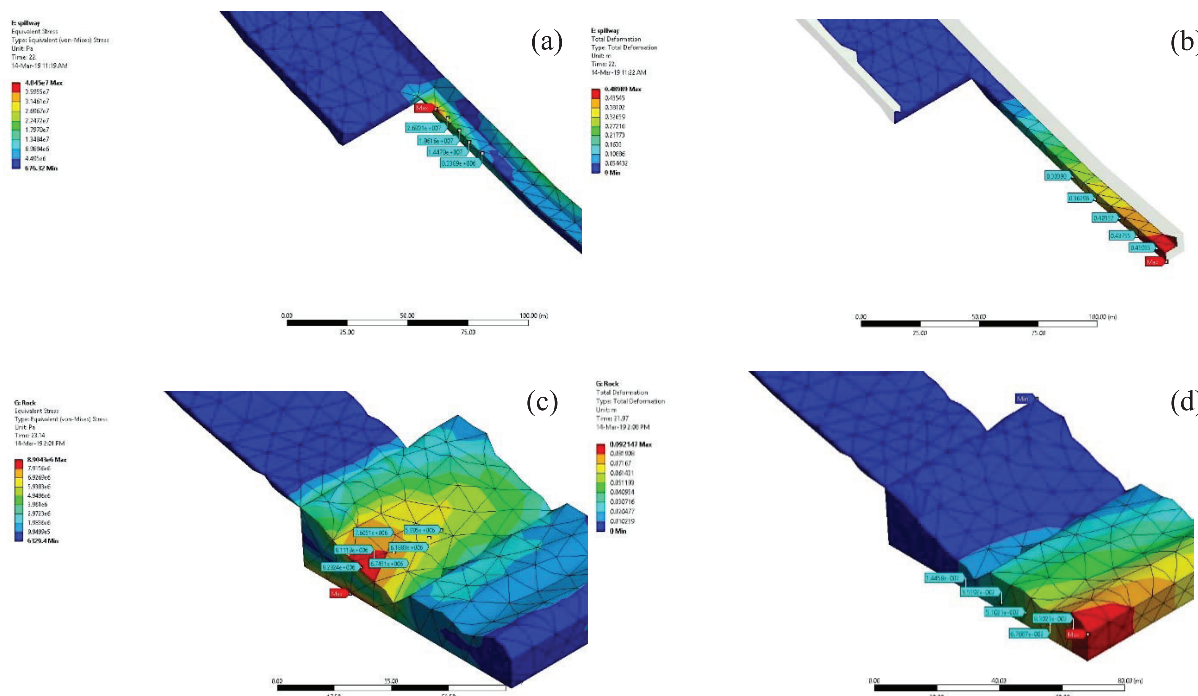

FIGURE 5. The distribution stress and deformation of the structure spillway for free surface water level of 155 m. (a) Stress of spillway, (b) Deformation of spillway, (c) Stress of downstream and (d) Deformation of downstream.

Figure 6 shows the effect of free surface water level of (a) stress and (b) deformation towards the spillway structure. It is seen that both stress and deformation of the spillway and downstream increased as the free surface water level increases. The maximum stress of the spillway and the downstream are 10.97 MPa and 40.4 MPa respectively. The region of high stress of the concrete for free surface level of 146 m at the spillway is lower than the compressive strength of concrete of 30 MPa. No structural failure is expected here. Whereas the stress for the free surface level of 155 m has exceeded the compressive strength of concrete. Precaution is needed if major rainfall happens. The high stress of 1.4 MPa and 8.9 MPa which were exerted from the free surface water level of 146 m and 155 m respectively which are lower than the compressive strength of the granite (130 MPa). However, the continuous interaction with water towards the structure will be affected in long term run due to erosion. Care must be taken to regularly check this area for any sign of crack that might propagate due to continuous interaction with water. As a safe measure, it is advisable to install energy dissipator to the spillway to ensure long-term safety of the dam structure.

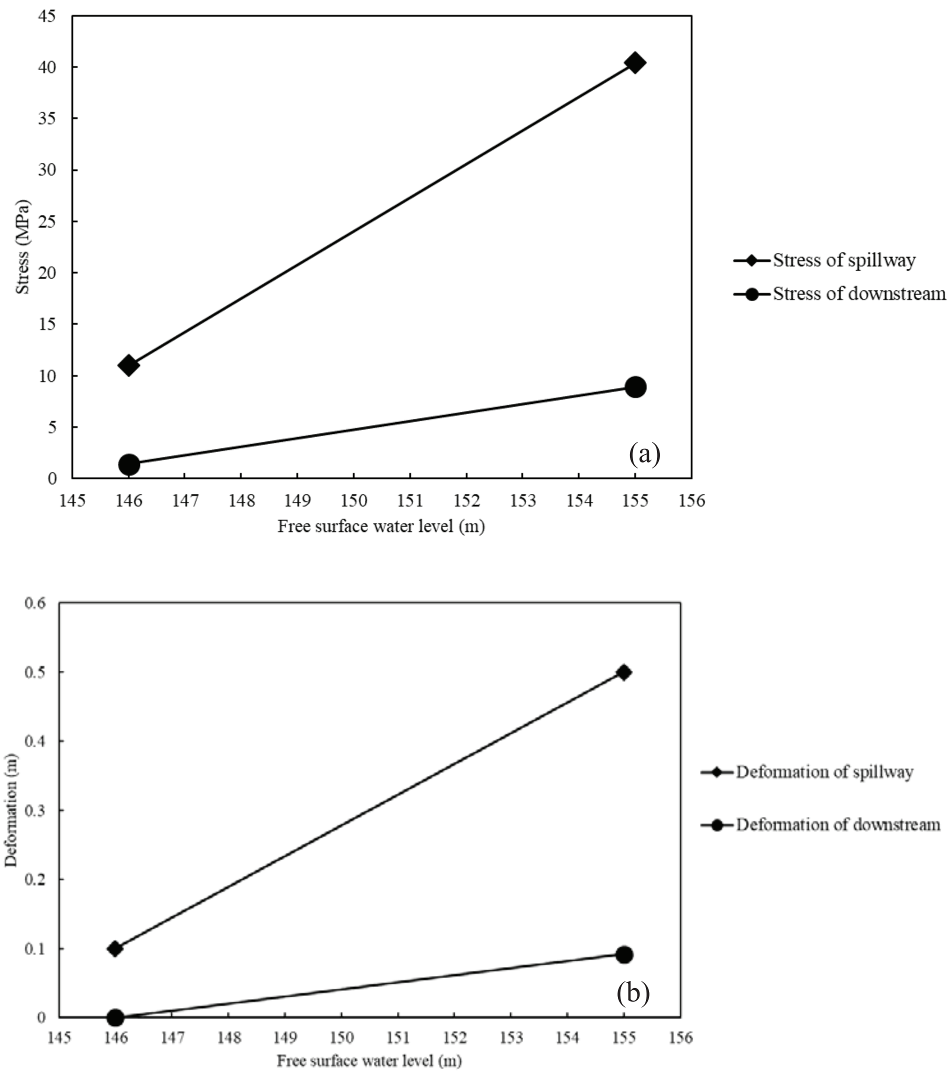

FIGURE 6. Effect of free surface water level of (a) stress and (b) deformation towards spillway structure.

CONCLUSION

From this study, the FSI analysis of the spillway Kenyir Dam has been successfully carried out. This paper enclosed the free surface water level in open channel condition and FSI simulation method to determine the forces exerted on the spillway structure. This study eventually reported that the highest force exerted on the spillway structure is at the 155 m free surface water level compared to the 146 m. The methodology outlined in the current paper benefit to future works relating to dam design and reliability analysis.

ACKNOWLEDGEMENTS

This paper by partly supported by the FRGS grant FRGS/1/2015TK03/USM/03/2 and Research University (RU) Grant 8014071 from Universiti Sains Malaysia.

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