Reliability analysis on the reservoir dam spillway structure using fluid-structure interaction

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Abstract. This paper presents a combined reliability and flow analysis on the spillway of reservoir dam using the numerical fluid-structure interaction (FSI) approach. The spillway is an important structure to the operation of reservoir dam, as it regulates the water flow from upstream to downstream. Therefore, a rapid discharge of water from the reservoir along the spillway will cause possibly flooding at downstream and incurs high structural stress. Using the ANSYS software, the two-way FSI problem of a dam spillway is numerically simulated. Such FSI numerical study able to simultaneously simulate and obtain both the parameters on fluid flow and structural deformation. The current study shows that the downstream has the highest flow velocity; while the highest deformation of 10.7 mm being observed in the connection bridge section. As the general stress level of the overall spillway structure (max. 30.75 MPa) is less than the yield stress of corresponding materials, the spillway will not exhibit any structural failure upon the current discharge mode.

Keywords: Dam; Fluid-structure interaction (FSI); Reliability analysis; Spillway structure; Stress

1. Introduction

Dam is a crucial infrastructure to the everyday need and development of civilization. It collects and holds water in the reservoir, for which the water supply to be distribute over several regions. Dam also function as river mitigation, reduces the occurrence of flooding during the rainfall season. Moreover, dam frequently build with a hydroelectrical power station. The upstream water flow from the reservoir dam will have its potential energy converted into kinetic energy in the turbine, which finally converted to useful electricity [1, 2].

Spillway structure is built in the dam to regulate the water flow and thus to control the water level of dam reservoir. Therefore, the spillway is an important structure to prevent overtopping of dam reservoir which may leads to dam failure and the flooding at downstream area. Other factors that causes to dam break includes the induced vibration [3]. Currently, the issue on dam failure is of particular interests among the researchers. This is coincident with the catastrophically consequences shall the dam failed, as it detrimental to human lives, infrastructure and social economy [4, 5].

Reliability analyses on the dam structures are essential as a part of maintenance works to prevent any failures during normal operating or overtopping conditions. A regular-timed reliability analysis not
reduce the risks of failures but also flawless dam operations, thus saving the costs and eliminate the incurs losses [6, 7]. In the past literatures, there are various numerical studies on the dam reliability being conducted. Particularly by the means of fluid-structure interaction (FSI) numerical approach. FSI enables the instantaneous tracking of fluid flow and structure deformation, thus a more accurate depiction of actual phenomenon. There are a few past literatures on the FSI study on the dam spillway structure [4, 5, 8]. The variation effect of sector gate opening were studied in Ref. [4, 5]; while the water flow along the spillway and downstream were numerically visualized in Ref. [8]. There is also a FSI reliability analysis being conducted to access the performance of dam banks operating at normal conditions [9].

This paper demonstrates the further application of FSI numerical scheme on the dam reliability analysis, particularly the spillway structure. In the present case, the free surface flow at the reservoir dam level is imposed. Lastly, the structural impact due to the water flow from reservoir was justified to determine for any possible cracking and failure.

2. Numerical simulation
Using the commercially available software, Ansys, the fluid-structure interaction (FSI) of dam spillway structure is numerically simulated. The associated primary modules are Fluent and Transient Structure, respectively for simulating the fluid flow and structural deformation [10, 11]. Both modules were later coupled and simultaneously solved by System Coupling module. For current study, two-way FSI is established by considering both the data transfers from fluid to structure and from structure to fluid. It is vital to consider a throughout two-way data transfer in the current reliability analysis to capture the realistic depiction of spillway flow problem by considering the relationship between water flow and structure deformation.

In the settings of Ansys Fluent, the three-dimensional water flow across the spillway is modelled to be incompressible, turbulence and unsteady. To track the instantaneous position of water flow, multiphase volume of fluid (VOF) model was employed with the implicit scheme. Meanwhile, the flow turbulence was modelled using the $k$-$\varepsilon$ turbulence model to enable the capture the turbulence properties of spillway flow. Whereas for the settings in Ansys Transient Structure, standard deformation model was applied. The material assignment on the spillway structure is shown in Figure 1. The connection bridge sector is made up of structural steel while elsewhere of the spillway is made up of concrete.

![Figure 1. Material assignments on the spillway structure.](image-url)
On the boundary conditions as shown in Figure 2, all the interfacial boundaries between fluid and structure are designated as no-slip wall and set to be fluid/structure interaction surfaces. At the upstream, the water is set to be at the ambient condition of atmospheric pressure equals to 0 Pa (gauge). The initial water level is set to be 10 feet above the ground level. The bottom part of the spillway structure is designated as fixed support. The modelling of gravity of magnitude 9.81 m/s\(^2\) is also enabled.

The unstructural mesh of optimized mesh sizing were generated on both the fluid and structural domains. In the System Coupling, the data transfers were created between fluid and structural domains. First order implicit upwind and coupled schemes were adopted for the current simulation. Finally, optimum time size was used to execute the two-way FSI simulation.

![Figure 2. Boundary conditions applied for the fluid/structure interactions study of spillway.](image)

3. Results and Discussion
This section depicts the FSI simulation findings on the reliability analysis of spillway structure. The high velocity region is observed at the spillway opening gap with a maximum value of 6.448 m/s and at the baffle block on the downstream spillway surface, as shown in Figure 3. Figure 4 shows the hydrostatic pressure across different upstream water levels. The deformation contour in Figure 5 shows that the connection bridge section sustained the largest deformation of 10.7 mm. However, such deformation appeared to be insignificant upon being experienced by the on-site personnel; thus negligible. Figure 6 depicts that the highest localized stress region at the sector gate being approximately 30.7 MPa. Meanwhile, the average nominal stress level on the spillway structure is within 10 – 20 MPa. As the maximal stress level of spillway structure is lower than the yield stress for structural steel of 370 MPa, no structural failure will be observed. Other sections of the spillway structure have stress level below 3.417 MPa, which is well below the yield stress of concrete of 20 MPa. Nonetheless, preventive care should be emphasized the high stress region, follows with regular maintenance to prevent the occurrence of cracking.
Figure 3. Velocity distribution of water flow along the spillway.

Figure 4. Pressure distribution of water along the upstream reservoir.
Figure 5. Deformation distribution of spillway structure.

Figure 6. Stress distribution of the spillway structure.
4. Conclusions
In this paper, the fluid-structure interaction (FSI) numerical reliability analysis of dam spillway was successfully simulated using the commercial software ANSYS. The investigated spillway structure was subjected to upstream water flow with water height of 10 feet. The water flow with highest velocity was observed on the downstream. For the structural aspect, the connection bridge section sustains highest deformation of 10.7 mm and averagely has highest regional stress. As the overall stress level in the spillway structure is far less than the yield strengths of steel and concrete, no structural failure will be observed. Generally, this study would benefit the reservoir dam sector for the prediction of dam failure. Subsequently, suitable countermeasures can be taken accordingly based on the result of reliability analysis.

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