Fluid/structure Interaction Numerical Study on the Mechanical Integrity of Water Dam Reservoir Banks

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Abstract. Dam reliability analysis is conducted to access the integrity of dam structure and thus to prevent dam failure. This paper presents the numerical reliability study of reservoir banks of water dam by the mean of fluid/structure interaction (FSI) simulation. Through FSI, the hydrostatics effect of the water in reservoir on the wall of dam was successfully simulated and identified. From the current numerical work, relatively stagnant water on the dam bank was observed, with the increasing water pressure along the water depth. Subsequently, localized high stress and deformation on the dam structure was successfully identified, and suitable countermeasures were being recommended. For the current investigated dam bank structure, the highest deformation and stress detected are respectively 1.185 mm and 3.12 MPa. Therefore, at present operating configuration, it is concluded the bank would not exhibit any failures.

1. Introduction

Dam is the most vital construction infrastructure to human civilization. It reserves water for daily usages and generation of electricity in hydro power plant. However, dam failure, such as dam break and overflow, can causes catastrophic damages, involving hundreds of human lives and their houses apart from economical losses. Therefore, it is common practice that the dam and reservoir are regularly maintained to prevent breakage and able to sustain the hydrostatics pressure [1, 2].

Various literatures had been reported in researching the dam reliability [3 – 11]. Most researchers utilized the numerical methodology to simulate the water flow in the dam and later investigate its structural reliability. Example of numerical scheme used in the dam simulation by past researches are: HEC-ResSim [3], finite element method (FEM) in ABAQUS [4], volume of fluid (VOF) method [5] and fluid/structure interaction (FSI) [6 – 11].

It was found that the FSI approach capable in capturing both hydrodynamic and mechanical parameters simultaneously. Therefore, FSI enables a more actual dam phenomenon being modelled numerically. FSI can be easily executed using the commercially available finite volume method (FVM)
software, ANSYS, using the packages of Fluent, Mechanical and System Coupling [12, 13]. Previous dam’s radial gates FSI simulations used the commercially available ANSYS software [6, 7, 8, 11]. Other than ANSYS, FSI simulation can also be implemented using in-house finite element code, SNACS [10].

In this paper, FSI study is conducted on the reservoir bank of a dam, to investigate the reliability of the concrete dam walls upon being exerted by the hydrostatics pressure. Various data (e.g. velocity, pressure, deformation and stress) will be analyzed to identify the reliability of dam and whether if any failure shall occur. The primary goal of current simulation work is to present the modelling of FSI phenomenon dam wall, which may be useful in predicting potential dam failure.

2. Governing equations

2.1 Fluid phase

In the current simulation of water flow in dam reservoir banks, the three-dimensional, incompressible Navier-Stokes equations were adopted with pressure-based solver. Incompressible Navier-Stokes equations decouple the energy equation by constraining the density to be constant, which is a reasonable assumption for the water. The emphasis of the simulation is on the pressures exerted on the dam structure and not the heat transfer. Hence, the energy equation could be decoupled from the mass and momentum equations without compromising the accuracy of the simulation results. With the energy equation discarded, the compact governing continuity and momentum equations can be respectively written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m,$$

(1)

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \cdot \vec{v}) = -\nabla p + \nabla \cdot \vec{t} + \rho \vec{g} + \vec{F}.$$

(2)

where the source term, $S_m$ is the mass added to the continuous phase from the dispersed second phase and any user-defined source, which is zero in the simulations; $p$ is the static pressure; the term of $\rho \vec{g}$ denotes the gravitational body force and $\vec{F}$ is the external body force (i.e. that arise from interaction with the dispersed phase). The stress tensor $\vec{t}$ is given by:

$$\vec{t} = \mu \left( \nabla \vec{v} + \nabla \vec{v}^T \right) - \frac{2}{3} \nabla \cdot \vec{v} I,$$

(3)

where $\mu$ is the molecular viscosity, $I$ is the unit tensor, and the term on the right-hand side is the effect of volume dilation.

The turbulence model employed was the standard $k$-$\varepsilon$ model [12]. The standard $k$-$\varepsilon$ turbulence model falls within the class of two-equation turbulence models which allow the determination of both, a turbulent length and time scale by solving two separate transport equations, as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \mu + \mu_t \frac{\partial k}{\partial x_j} \right] + \frac{G_k}{\varepsilon} (\rho u_i - \rho \vec{g} - \rho \vec{F}) + S_k,$$

(4)

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \mu + \mu_t \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k - C_{3k} G_b) - C_{2\varepsilon} \frac{\varepsilon^2}{k} + S_{\varepsilon}.$$

(5)

In equations (4) and (5), $G_k$ represents the generation of turbulence kinetic energy due to the mean velocity gradients, $G_b$ is the generation of turbulence kinetic energy due to buoyancy and $Y_M$ represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. Additionally, $\sigma_k$ and $\sigma_{\varepsilon}$ are respectively the turbulent Prandtl’s numbers for $k$ and $\varepsilon$; $S_k$ and $S_{\varepsilon}$ are user-
defined source terms and lastly with constant terms of $C_1\varepsilon$, $C_2\varepsilon$ and $C_3\varepsilon$. Detailed interpretations of these terms and their formulation are provided in the ANSYS Fluent documentation [12].

Subsequently, to account for the air-water interactions in the dam simulation, the multiphase Volume of Fluid (VOF) model was employed. VOF can model two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each of the fluids throughout the domain. The volume fraction equation is given as:

$$\frac{1}{\rho_q} \left[ \frac{\partial}{\partial t} \left( \rho_q \rho_u \vec{v}_q \right) + \nabla \cdot \left( \rho_u \rho_u \vec{v}_q \vec{v}_q \right) \right] = \nabla \cdot \left( \frac{\vec{m}_{pq} - \vec{m}_{qp}}{\rho_u} \right), \tag{6}$$

where $\vec{m}_{qp}$ is the mass transfer from phase $q$ to phase $p$ whereas $\vec{m}_{pq}$ is the mass transfer from phase $p$ to phase $q$.

### 2.2 Structural phase

The structure simulations were carried out with ANSYS Mechanical [13]. After the pressure loads were acquired from the fluid simulations, the results were fed as input to static structural analysis for the dam gates. For static linear analyses, ANSYS Mechanical APDL applied the following equation:

$$[K][u] = \{F^a\} + \{F^r\}, \tag{7}$$

where $[u]$ is the nodal degree of freedom (DOF) vector, $[K]$ is the total stiffness or conductivity matrix, which defined as

$$[K] = \sum_{m=1}^{N} [K_e], \tag{8}$$

with number of elements, $N$ and element stiffness or conductivity matrix, $[K_e]$. On the right hand side of equation (7), $\{F^r\}$ is the nodal reaction load vector and $\{F^a\}$ is the total applied load vector, which is the sum of applied nodal load vector, $\{F^{nd}\}$ and total of all element load vector effects (pressure, acceleration, thermal, gravity), $\{F^e\}$:

$$\{F^a\} = \{F^{nd}\} + \{F^e\}. \tag{9}$$

Finite element (FE) procedures are applied on all structural models by ANSYS Mechanical to generate system of simultaneous linear equations which have been described in the previous section. These equations are then solved by either a direct elimination process or an iterative method. As in current dam simulation, the Preconditioned Conjugate Gradient (PCG) solver was chosen.

PCG solver is one of the three iterative methods available in ANSYS Mechanical APDL which is efficient and reliable for all types of analyses including the ill-conditioned beam/shell structural analysis. The PCG solver is only valid for real symmetric stiffness matrices. To solve typical system of equations in the form of previous equation iteratively, general CG methods cast the solution in the form of a series of vectors $\{p_1\}$:

$$\{u\} = \alpha_1\{p_1\} + \alpha_2\{p_2\} + \alpha_3\{p_3\} + \cdots + \alpha_m\{p_m\}. \tag{10}$$

### 3. Numerical simulations

The fluid/structure interaction (FSI) of water flow and dam’s reservoir bank (as in Figure 1) is numerically simulated using the commercially available software, ANSYS. The three-dimensional flow is regarded as incompressible, unsteady and turbulence. In FLUENT settings, $k-\varepsilon$ turbulence model and multiphase VOF model were applied together with the pressure-based solver. Besides, the implicit time scheme is employed, with fixed time step of 0.01 s being chosen for the transient flow simulation. In the
System Coupling, data transfers were created for all the fluid-structure interaction regions for both fluid and structural domains.

![Figure 1](image1.png)

**Figure 1.** Geometrical details of the dam’s reservoir bank.

For the aspect of boundary conditions (BCs) considered, the flow inlet is set as the velocity inlet of 1.0 m/s; while the flow outlet is designated as the pressure outlet at ambient atmospheric pressure of 1 atm. Subsequently, the fluid/structure surfaces are set as no-slip walls. Gravity is being considered with magnitude of 9.81 m/s² to mimic the actual application and thus account for the hydrostatics effect. On other hand, for the BC in structural domain, the base of reservoir bank is set to be fixed support such that it would remain stationary throughout the flow; and fluid-structure interaction (FSI) for the solid structure surface that in contact with the fluid phases. The phases that exist in the fluid domain are air and water, with both at temperature of 25°C and pressure of 1 atm. In multiphase VOF scheme, the primary phase is air and secondary phase is incompressible water. The dam is made of concrete material with Young modulus of 5.53 GPa, density of 2300 kg/m³, tensile ultimate strength of 5 MPa and Poisson’s ratio of 0.18. While the material properties of air and water are specified in the material data library of ANSYS. Due to the complexity of the geometry, hybrid unstructured meshes (consists of the hexagonal and tetrahedral meshes) were generated for both the fluid and structural domains (refers Figure 2). The mesh resolution is set at fine, to balance off both the accuracy and computational time.

![Figure 2](image2.png)

**Figure 2.** Generated hybrid mesh for the structural reservoir bank.

4. Results and Discussion
The fluid/structure interaction (FSI) simulation on the reservoir bank had yielded various hydrodynamics data (velocity and pressure) and mechanical data (deformation and stress). In Figure 2,
the velocity of water in the reservoir is found to be within the range of 0 m/s (completely stagnant water) to 4.5 m/s. Such nearly stagnant flow is due absent of overtopping flow and the water remains in the reservoir. These stagnant waters stored in the reservoir would be exerted hydrostatics pressure to the wall of the dam, which as shown in the Figure 3. The pressure gradually increases as it gradually descends to the base of the dam, as depicted in Figure 4.

On the structural aspect, the deformation contour in Figure 5 shows that there is a localized high deformation region with value of 1.185 mm. Such high deformation is occurred at the dam section divider. Therefore, regular maintenance and checking must be conducted particularly on this region, for any sign of crack propagations. Besides, the stress contours on Figure 6 revealed that the walkway linking the reservoir bank and bottom outlet exhibited highest stress. Furthermore, from the cross-sectional cut in Figure 6, it is found that the interior part of the dam has slightly higher stress compared to that at the dam outer surfaces. However, the maximal stress of the whole reservoir dam is identified as 3.12 MPa, which is substantially lower than the concrete yield stress of 20 MPa. Therefore, the reservoir bank of the dam would not fail, at current present state of water level and flow.

Figure 3. Velocity contour of the water flow near the reservoir bank.

Figure 4. Gauge pressure contours of the water flow near the reservoir banks. The right contour depicts the pressure distribution of water on the dam wall.
Figure 5. Deformation contours (in unit meter) of the reservoir bank’s concrete wall. The right contour depicts the cross-sectional cut of dam wall where high deformation being recorded.

Figure 6. Stress contours (in unit Pa) of the reservoir bank’s concrete wall. The right contour depicts the cross-sectional cut of the dam wall, to visualize the interior stress.

5. Conclusions
By means of fluid/structure interaction (FSI), that utilized both multiphase VOF and $k$-ε models, both the hydrodynamic and mechanical aspects of reservoir bank of a dam had been successfully investigated. The water profile is found to remain relatively stagnant due to the absent of overtopping. Besides, the water pressure exerted on the wall of dam is gradually increasing toward the base of the reservoir. A high deformation of 1.18 mm is noticed on the section divider of the dam. However, the overall stress level of the dam upon exerted by the water reservoir is well below the yield stress of concrete, such that it would not fail. Generally, through the detailed FSI numerical approach, the mechanical reliability aspect of the reservoir bank of a dam can be studied alongside with the fluid flow of water in the dam. Moreover, the FSI numerical simulation was demonstrated viable for the dam reliability study.

6. References
[1] L M Sidek, F C Ros and N H A. Aziz 2011 Student Conference on Research and Development
[2] S Solava and N Delatte 2003 Proceedings of the Third ASCE Forensics Congress
[3] G Uysala, B Akkol, M. Irem Topcu, A. Sensoy and D. Schwanenberg 2016 Procedia Engineering 154 1385–92.
[4] Q Zhang, D Li, F Wang and B Li 2018 Engineering Failure Analysis 91 72–91
[5] A. Issakhov, Y. Zhandaulet and A Nogaeva 2018 International Journal of Multiphase Flow
[6] F C Ng, A Abas, I Abustan, Z M R Rozainy, M. Z. Abdullah, A. B. Jamaludin and S. M. Kon 2018 IOP Conf. Ser. Mater. Sci. Eng. 370(1) 012062
[7] F C Ng, A Abas, I Abustan, Z M R Rozainy, M. Z. Abdullah, A. B. Jamaludin, and S. M. Kon 2018 IOP Conf. Ser. Mater. Sci. Eng. 370(1) 012063
[8] M N Nashurdin, A Abas, A Azman, F C Ng, M R M Radzi and A Hassani 2019 *AIP Conference Proceedings* **2129** 020044

[9] N. Cheraghi-Shirazi, A.R. Kabiri-Samani and B. Boroomand 2014 *Flow Measurement and Instrumentation* **40** 91–8

[10] O Omidi and V Lotfi 2017 *Journal of Fluids and Structures* **69** 34–55

[11] T B Amina, B Mohamed, L André and B Abdelmalek 2015 *Engineering Structures* **84** 19–28

[12] ANSYS Fluent Documentation 2017 *ANSYS Inc.*

[13] ANSYS Mechanical Documentation 2017 *ANSYS Inc.*

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