Effect of the gap height of radial gate on the volumetric flow rate in dam

Fei Chong Ng¹, Aizat Abas²*, Ismail Abustan³, Z. Mohd Remy Rozainy³, MZ Abdullah⁴, Ali b. Jamaludin⁵, Sharon Melissa Kon⁶

¹,²School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, 14300, Penang.
³School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, 14300, Penang.
⁴School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, 14300, Penang.
⁵TNB Research Sdn. Bhd., No. 1, Lorong Ayer Itam, Kawasan Institusi Penyelidikan, 43000 Kajang.
⁶School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, 14300, Penang.

*Corresponding author: aizatabas@usm.my

Abstract. This paper investigates how the variation of gap height of radial gate in scaled down dam would affect the volumetric flow rate. Both fluid/structure interaction (FSI) numerical simulation and experimental works on a scaled-down dam model were conducted, eventually both approaches yield results with discrepancy not exceeding 9.63%. For 10 mm and 12 mm gap, lowest water flow rate is being observed in the Gate 2 compared to Gate 1 and Gate 3. Conversely, the Gate 2 registered highest water flow rate for gate with gap of 8 mm. Generally, it is found that the volumetric flow rate increases along with the increase with the gap height of radial gate. Moreover, the volumetric water flow rate in actual dam also be determined using Reynolds number.

1. Introduction

Dams are important projects for developing countries, because the population receives domestic and economic benefits from the investments [1]. However, the potential energy of the water reservoir can cause considerable damage if the dam fails [2]. During the events of dam failure, huge volume of impounding water together with immense potential energy stored in it will pound the immediate downstream areas, endangering lives, damaging properties along its path and eventually result in widespread flooding [3]. Therefore, careful planning and consistent monitoring are required for the design and construction of dams [4].

In the past, there have been various researchers that simulated the flow of water in dam, for instances MIKE 11 1-D hydrodynamic model [2, 5], smoothed particle hydrodynamics (SPH) model [6 – 9] and fluid/structure interaction (FSI) [10, 11]. Among these approaches, the FSI simulation has...
proven to be more reliable as it able to capture both aspects of fluid flow and structural deformation in the modelling.

To the best knowledge of the authors, research was rarely being conducted to determine the water flow front across the radial gates of dam. Essentially, the current paper would reveal the unique numerical FSI and experimental approaches that allow researchers to study the water flow rate in dam without huge expenses.

2. Simulation
The scaled-down dam model and its corresponding fluid domain after mesh are depicted in Figure 1. The dimensions of the fluid domain are 3021.4 mm (length) × 2000 mm (width) × 600 mm (height). Tetrahedral mesh with their mesh elements being optimized were adopted in present simulation. Such optimized mesh enables both low computational cost at reasonable good numerical accuracy to be achieved.

The general boundary conditions (BC) used in current simulation are as summarized in Figure 2. For the mixture phase of the inlet, velocity inlet boundary conditions are used to define the velocity and scalar properties of the flow. The velocity of the water flow into the inlet, \( v_{\text{inlet}} \) is set at 0.01 m/s; while no-slip wall condition being imposed such that the wall-fluid velocity is 0 m/s. Moreover, the pressure at the inlet and outlet equal the atmospheric pressure.

System Coupling module were used to couple both Transient Structural and Fluid Flow (FLUENT). System to achieve two-way data transfers between the structural region and 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 current simulation is set at 0.1 s and the end time is 5 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 structural domain (left) and fluid domain (right).](image1)

![Figure 2. Summarized boundary conditions (BC) used in the numerical simulation.](image2)
3. Experiment

The experiment is conducted on the scaled-down physical dam model as shown in Figure 3 that located in the Civil School Research Lab. When water flows through the gap underneath the radial gates, force is exerted on the gate surface. The purpose of the experiment is to find out the water flow rate across the radial gate of the dam, to be subsequently compared with simulated data.

Firstly, the apparatus is set up at radial gate 1 for the following configuration as in Figure 4: (i) upstream head, $h_1 = 80$ mm; (ii) gap height or discharge height, $h_2 = 8$ mm. Then, the sensor is placed in the center of the gap beneath the radial gate and connected to the EASZ-10P Doppler Flowmeter (see Figure 5). It is used to measure the flow rate of water in a non-intrusive principle with a high speed 16-bit microprocessor unit. Once the flow rate at the radial gate 1 is taken, the measurement is continued at radial gate 2 and then 3. The experiment is repeated for gap height or discharge height, $h_2 = 10$ mm and $12$ mm.

![Figure 3. Physical scaled-down dam model.](image)

![Figure 4. Position of gap or discharge height, $h_2$ and upstream head, $h_1$ for the physical model.](image)
4. Results and Discussions

Figure 6 shows the volume fraction of water flow near the radial gate of various gap heights. Qualitatively there are more water flow front the gates of dam when the gap heights being increases. From simulation data, the water velocity at the gap of the radial gate were averaged out at three different locations to obtain its mean value near each three gates. Subsequently the flow rate of water exiting the dam is calculated. Later the simulated water flow rates for each gate at different dam cases were compared to the corresponding experimental data on water flow rates, and presented in Figure 7. The simulations also revealed that the increases in the gap height of radial gate, the volumetric flow rate of water on all three gates also increases. Based on Figure 7, it can be seen that the volumetric flow rates of water obtained from both simulation and experiment are similar. The smallest percentage difference is 1.26% for water flowing through Gate 2 with a gap of 10 mm whereas the biggest percentage difference is 9.63% for water flowing through Gate 3 with a gap of 8 mm. The differences are acceptable as they are less than 10%. Several factors such as geometry, physics set up and boundary conditions are taken into consideration to ensure that the simulation model is similar to the experimental model.

Through the dimensionless number analysis, the volumetric flow rate at actual-sized dam can be determined. Table 1 gives the dimensions of both actual dam and the scaled-down dam models used in both experimental and simulation works.
Figure 7. Plots of experimental (red) versus simulation (blue) water flow rates, across the radial gate of different gap heights (8 mm, 10 mm and 12 mm).

Table 1. Dimensions of actual and scaled-down dam models.

| Dimension                  | Actual dam | Scaled-down 1/25 dam |
|----------------------------|------------|----------------------|
| Length                     | 75535 mm   | 3021.4 mm            |
| Width                      | 24136.5 mm | 965.46 mm            |
| Height                     | 12000 mm   | 480 mm               |
| Length of one radial gate  | 12193 mm   | 487.72 mm            |

At ambient temperature of 28°C, the water kinematic viscosity is 0.8355 m²/s. The dam model is assumed to be a rectangular duct with an open channel flow, thus the characteristic length, \( L \) is known as hydraulic diameter, \( d_h \). The equation of hydraulic diameter is:

\[
L = d_h = \frac{4A}{u} = \frac{4(\text{width})(\text{height})}{2(\text{width} + \text{height})} \tag{1}
\]

where \( A \) is the cross sectional area of the duct and \( u \) is the wetted length. The value of \( d_h \) for the physical model is 0.6412 m while the real dam is 16.0302 m. Using Reynolds number similarity for both scaled-up model and actual dam, the volumetric flow rate at real dam can be computed, as given in Table 2. Eventually the actual volumetric flow rate at real dam is 25 times larger than in the 1/25 scaled-down model. The Reynolds numbers of the water flow in both dams are the same. Again, it is seen that the dam with radial gate of height 0.3 m possess the highest flow rate of 156.4 L/s.
### Table 2. The actual water flow rate in dam, calculated using Reynolds number.

| Gap Height (m) | Average water velocity at physical model (m/s) | Average water velocity at real dam (m/s) | Volumetric flow rate at real dam (L/s) | Reynolds number |
|----------------|-----------------------------------------------|----------------------------------------|----------------------------------------|----------------|
| 0.008          | 1.1906                                        | 0.0476                                 | 116.1                                  | 913727         |
| 0.010          | 1.1535                                        | 0.0461                                 | 140.5                                  | 885263         |
| 0.012          | 1.0691                                        | 0.0428                                 | 156.4                                  | 820490         |

5. Conclusions

This paper had presents both scaled-up experimental and numerical simulation approaches to analyze the volumetric flow rate of water across the radial gates of dam. Both methodologies eventually gave findings of relative close, with deviation not more than 10 %, affirming the results. It is reported that the water flow rate is the highest at larger gap height of the radial gate. Additionally, through Reynolds number invariant, the volumetric flow rates at real dam were determined, and the highest water flow of 156.4 L/s being recorded in 0.3 m height dam.

Acknowledgements:

The authors gratefully acknowledged the financial support provided by Institute of Postgraduate Studies (IPS), Universiti Sains Malaysia (USM), through the USM Fellowship 2017 scheme. Additional, this work was also partly supported by the Short Term Grant 60313020 from the Division of Research and Innovation, Universiti Sains Malaysia, and FRGS Grant 6071322 from the Ministry of Higher Education.

References:

[1] International Commission of Large Dams, ICOLD (2011); “Role of Dams”. Available from: <www.icold-cigb.net>. [Extracted at 11 March 2017]

[2] Solave and Delatte (2003), “Lessons from the Failure of the Teton Dam”, Proceedings of the 3rd ASCE Forensics Congress, San Diego, California.

[3] L. M. Sidek, F. C. Ros and N. H. A. Aziz (2011), “Numerical Modelling of Dam Failure for Hydropower Development in Cameron Highlands – Batang Padang Scheme, Pahang Malaysia”, Student Conference on Research and Development, Universiti Tenaga Nasional, Selangor, Malaysia.

[4] Energy Education on Dam failures. Available from: http://energyeducation.ca/encyclopedia/Dam_failures. [Extracted at 3 June 2017]

[5] Razad, A. A., & Ros, F. C. (2009). One Dimensional Dam Breach Modelling for Proposed Hydropower Development in Ulu, (October).

[6] Gomez-Gesteira, M. (2009). State-of-the-art of classical SPH for free-surface flows. Journal of Hydraulic Research, 48(extra), 0. Available from: <https://doi.org/10.3826/jhr.2010.0012>. [Extracted at 11 March 2017]

[7] Benedict, D., Crespo, A. C., Dominguez, J. M., Barreiro, A., & Go, M. (2011). GPUs, a New Tool of Acceleration in CFD: Efficiency and Reliability on Smoothed Particle Hydrodynamics Methods, Universidade de Vigo, Ourense, Spain and University of Manchester, Manchester, United Kingdom. Available from: <https://doi.org/10.1371/journal.pone.0020685>. [Extracted at 11 March 2017]

[8] Gomez-Gesteira, M. (2009). State-of-the-art of classical SPH for free-surface flows. Journal of Hydraulic Research, 48(extra), 0. Available from: <https://doi.org/10.3826/jhr.2010.0012>. [Extracted at 11 March 2017]

[9] Benedict, D., Crespo, A. C., Dominguez, J. M., Barreiro, A., & Go, M. (2011). GPUs, a New Tool of Acceleration in CFD: Efficiency and Reliability on Smoothed Particle
Hydrodynamics Methods, Universidade de Vigo, Ourense, Spain and University of Manchester, Manchester, United Kingdom. Available from: <https://doi.org/10.1371/journal.pone.0020685>. [Extracted at 11 March 2017]

[10] Gómez-Gesteira, M and Dalrymple, RA 2004 J Waterw Port Coast Ocean Eng 130(2) 63

[11] Mfundu Vesi (2014). Dynamic Modelling of Arch Dams in the Ambient State, University of Cape Town, Cape Town, South Africa.