NUMERICAL INVESTIGATION OF ENERGY DISSIPATION IN STEPPED SPILLWAY USING VARIOUS MULTIPHASE MODELS

B.R. PANDEY AND G. ZENZ

Institute of Hydraulic Engineering and Water Resources Management, TU Graz, Graz, Austria

M.R. K C AND B. CROOKSTON

Utah Water Research Laboratory, Utah State University, Utah, USA

ABSTRACT

The safety of dams relies significantly on managing spillway flows, especially during large hydraulic events. Stepped spillways serve the purpose of safely conveying flood water downstream while also dissipating large amounts of kinetic energy. In this study, CFD modeling of a stepped spillway was performed using ANSYS Fluent, and the results were validated against the results of physical model experiments conducted in the Utah Water Research Laboratory at Utah State University. The physical model consisted of a stepped spillway having a slope of 18.4o with a uniform step height of 0.2 m. Homogenous and non-homogenous multiphase models were implemented, considering Volume of Fluid (VOF)-Sharp, Mixture-Dispersed, and Eulerian-Dispersed interface tracking techniques model available in the ANSYS Fluent solver. The physical model results of air concentration, flow velocities, and water surface profile for two different flow rates were evaluated using the numerical model for validation. Additional flow rates were also investigated along with step heights of 0.2 m and 0.1 m. The results revealed that the VOF-Sharp interface tracking model struggled to entrain air into the flow whereas the Mixture and Eularian models displayed aerated flow. Regardless, the VOF-sharp interface tracking model was found to be more suitable for stratified flow with a sharp interface between air and water. The Mixture model was utilized for further analysis with different step heights and flow rates. Air concentration (C) and velocity (V) profiles at selected step edges were compared against the experimental results. Velocity profiles were in close agreement with the experimental results whereas the CFD model consistently overpredicted air concentration. The dispersed interface tracking method demonstrated suitability for highly disturbed skimming flow, underscoring the importance of selecting appropriate models for investigating and analyzing flow over stepped spillways. The length of the inception point increased whereas rate of energy dissipation decreased with increasing discharge over the chute. This implies the necessity of detailed design and safety evaluation of flood discharges for appropriate chute design.

***Keywords**: CFD modeling, stepped spillway, VOF, Mixture, Eulerian, air concentration, velocity, energy dissipation.*

1 INTRODUCTION

Spillways are susceptible to damage during severe flooding events, threatening dam integrity. The incident at the Oroville dam, where the spillway sustained damage during a high flood event, is a prototypical example of such occurrences (Koskinas et al., 2019). The hydraulic performance of a spillway is intricately linked to its design type. Stepped spillways with varying geometries have been extensively examined and constructed to reduce flow velocity and minimize stilling basin damage. Several studies by Boes & Hager (2003), Pfister & Hager (2011), Gonzalez (2004), and Baylar (2006) including the work of Chanson (2001) have led to a comprehensive understanding of the hydraulic performance of the stepped spillways.

In recent years, advancements in numerical techniques and computational power have increased interest in numerical modeling of flows for engineering applications, offering greater flexibility in design variations. Dastgheib et al. (2012) carried out a numerical study using the RNG turbulent model to evaluate the energy dissipation over a stepped spillway. The results were compared to the experimental data set for flow velocity at the end of the steps and found to be comparable, illustrating the capabilities of numerical simulation. Saqib et al. (2022) studied the pressure fluctuation and energy dissipation for curved steps using the renormalization group -RNG turbulence model through Flow3D.

Curved treads of the steps were found to be more effective in terms of energy dissipation for low flow rates. The negative pressure was also found to be more for curve steps. Li et al. (2018) implemented the numerical method using a realizable k-ε turbulence model for eight-step configurations. The sharp and rounded steps were found to have a high rate of air concentration as compared to the baffled-shifted rounded configuration. The lowest turbulent dissipation rate was obtained with the higher residual head considering the baffled-shifted rounded configuration. Jahad et al. (2024) studied compound slopes over a stepped spillway implementing a realizable k- ε model to evaluate the total kinetic energy. Five different geometrical setups were tested. The compound slope steps resulted in higher turbulent kinetic energy increasing the operational efficiency of the spillway. Jahad et al. (2024) carried out several tests concerning the energy dissipation efficiency through CFD simulations using the k- ε turbulent model, the result illustrated a higher energy dissipation rate for curved slope steps of about 10.5%. Recently Pandey et al. (2024) investigated the influence of different geometrical variations of the steps using multiphase models using ANSYS Fluent. Results showed that the energy dissipation rate was higher for smaller flow rates and decreased with increasing flow rates. Similarly, vertical square-edged steps showed better energy dissipation than the pooled or reverse-sloped steps.

This paper investigates various multiphase numerical model approaches using Ansys Fluent solver. The results are compared with a physical model test of a stepped spillway with a mild slope of 3H:1V, conducted in the Utah Water Research Laboratory at Utah State University as shown in **Figure 1**. The study used two uniform step heights: one with a height of 0.2 m and a length of 0.6 m, and another with a height of 0.1 m and a length of 0.3 m. Numerical modeling was carried out for eight different flow rates (0.285, 0.425, 0.565, 0.705, 0.845, 0.985, 1.125, 1.265 $m^3/s/m$) were evaluated to assess their impact on energy dissipation efficiency for the two different step heights.

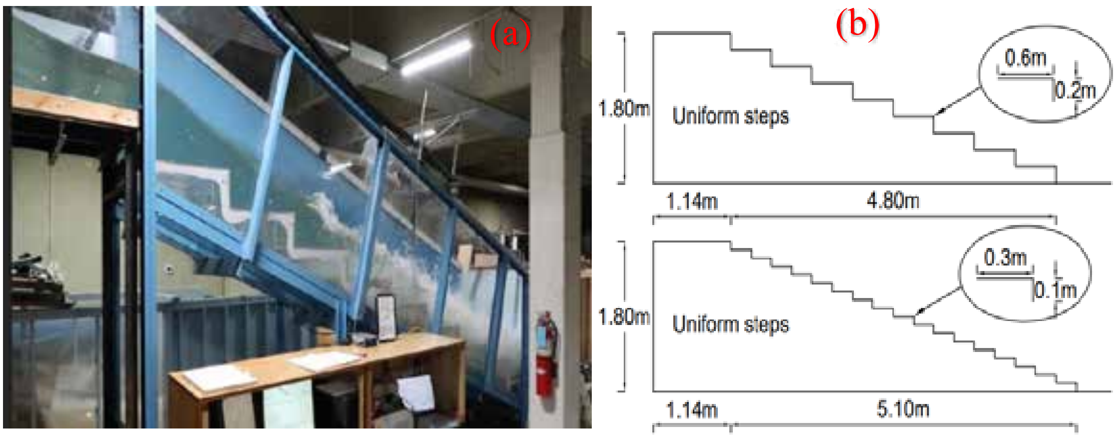

Figure 1: Physical setup for experimental investigation (a) and geometric details of stepped spillway (b)

2 Methodology

A numerical investigation was carried out using different multiphase models through ANSYS Fluent. The VOF-sharp interface, Mixure-dispersed interface, and Eulerian-dispersed interface were implemented. The VOF-sharp interface model is generally used for free surface stratified, large bubble motion, and sloshing flows. The Mixture-dispersed interface model and Eulerain-dispersed model are used for highly disturbed flows such as bubbly, and slurry flows. The details of the multi-phase models have been discussed in the reference manual of ANSYS, Fluent (2023).

2.1 Model comparison

The model comparison was made between the VOF-sharp interface, the Mixure-dispersed interface, and the Eulerian-dispersed interface. **Figure *2*** shows the multiphase model results over the uniform steps of 0.2 m height and 0.6 m length for the discharge of 0.425 $m^3/s/m$. The results illustrate that the VOF-sharp interface model was unable to capture the mechanism of self-entrainment of air into the flow. The Mixture-dispersed interface and the Eulerian-dispersed interface were able to show aeration of the flow as expected in self-aerated stepped spillway skimming flow. For consistency among all model results, the inception point was considered as the step edge near which the air volume fraction reached a value of 0.09 to 0.18. The Mixture-dispersed interface model was adopted for further model simulation to reduce the computational cost, as solving full Eulerian-dispersed interface equations for several test run cases was found to be costly in terms of run time simulation.

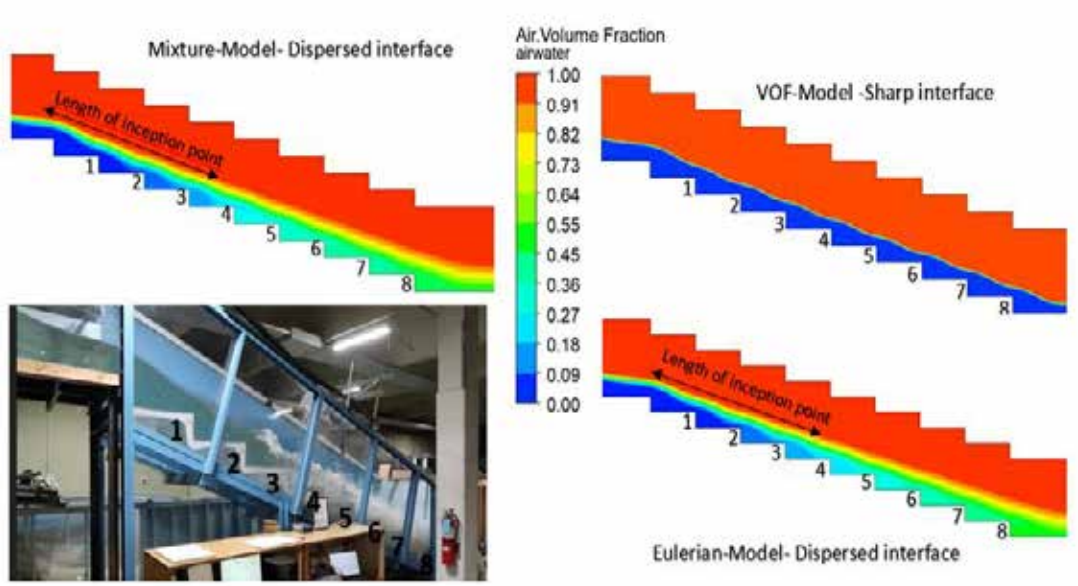

Figure 2: Simulated air-water flow field for specific discharge of 0.425 m^3/s /m using different multiphase models.

2.2 Mesh sensitivity analysis

Mesh sensitivity analysis is a crucial tool for evaluating how the discretization of the numerical domain affects simulation outcomes. To this end, three different grid sizes were examined: fine (0.005 m), medium (0.008 m), and coarse (0.01 m). The water surface elevation over the spillway crest (see **Figure 3**) and depth average velocity at step 8 (see **Table 1**) were compared for different mesh sizes, for the flow rate of 0.565 m^3/s/m. The free water surface above the weir crest was less affected by the grid size and compared well with the experimental observations.

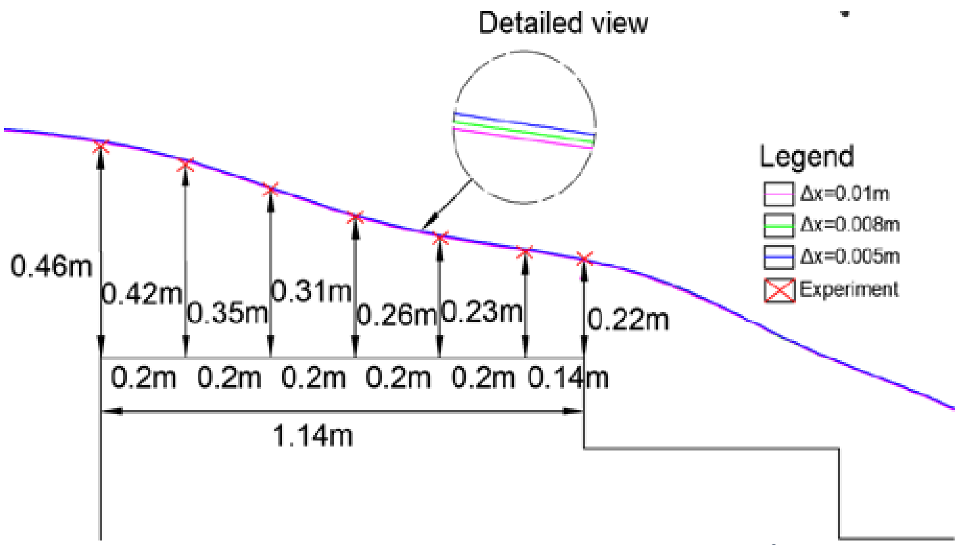

Figure 3: Model mesh comparison for flow rate of 0.565 m^3/s/m

The depth average velocity was estimated with the relation of clear water depth, Chanson (1996):

$$y_{clear} = \int_0^{y_{90}} (1 - C) * dy \qquad (1)$$

$$V = q / y_{clear} \qquad (2)$$

Where V is the depth average velocity, q is the specific discharge and y_{clear} is the equivalent clear water depth.

Table 1: Depth average velocity at 8th Step for flow rate of 0.565 $m^3/s/m$

Mesh size	Velocity (m/s)
0.005m	5.10
0.008m	5.16
0.01m	5.28
Experiment	**5.12**

A mesh size of 0.005 m was adopted for further simulations which represented a minimum absolute error of 0.39% for depth average velocity.

2.3 Model Mesh

The adopted mesh model of grid size 0.005 m with boundary conditions has been presented in **Figure 4**.

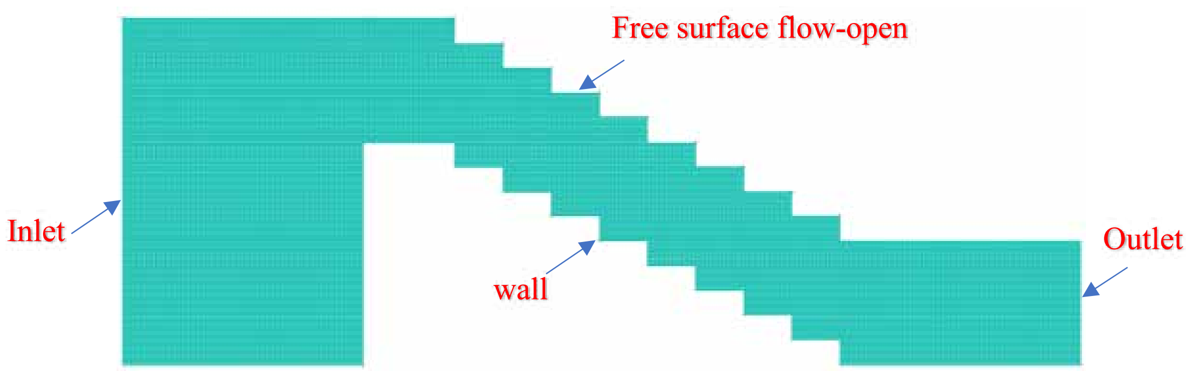

Figure 4: Model mesh with a grid size of 0.005m representing boundary conditions

2.4 Model validation

The model validation was carried out for two flow rates of 0.425 and 0.565 $m^3/s/m$. The water surface elevation at the crest as shown in ***Figure 5*** and dimensionless velocity distribution with V/V_{90} as presented in ***Figure 6*** were compared with the experimental data sets. V_{90} is the velocity at a depth of 90% air concentration. The flow velocities were compared in the highly aerated zone at step 7th for both of the flow rates.

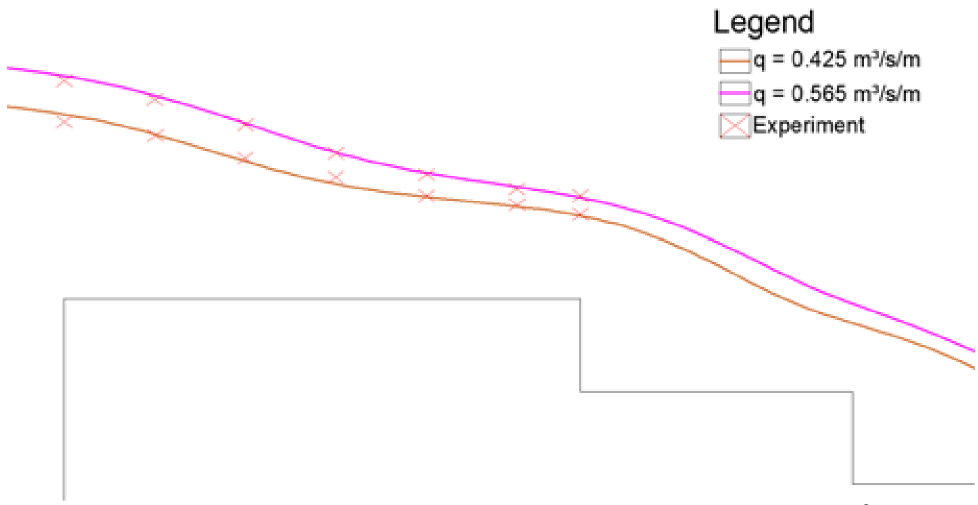

Figure 5: Water surface elevation for a flow rate of 0.425 and 0.565 $m^3/s/m$

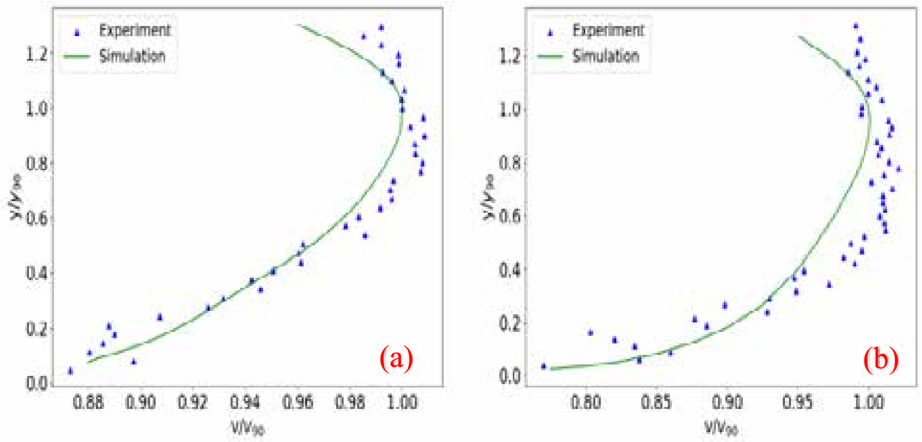

Figure 6: Dimensionless velocity distribution at step 7th for a flow rate of 0.425 (a) and 0.565 (b) m^3/s/m

The water surface elevations for adopted flow rates were found to be more or less similar to the experimental point elevation measurements along the crest of the spillway. The dimensionless flow velocities distribution along the vertical depth at step 7th also followed a similar distribution with the experimental data set. The validated model was further tested with different flow rates to evaluate the impact of higher flow rates.

3 Result and Discussion

Uniform step heights of 0.2 m with lengths of 0.6 m & 0.1 m height and length of 0.3 m were tested with eight different discharges (i.e, 0.285, 0.425, 0.565, 0.705, 0.845, 0.985, 1.125, and 1.265 m^3/s/m). The influence of incremental discharge over the steps for change in the location of the inception point, turbulent kinetic energy (TKE), and energy dissipation efficiency were studied.

3.1 Inception point

Inception point is a location along the chute at which self-aeration of the flow starts. This point divides the flow into an upstream clear water region and a downstream aerated region. A shorter clear water region over the steps reduces the risk of cavitation as the entrained air reduces the chances of cavitation. The impact of incremental discharge on the location of the inception point was tested over two different step heights. The flow rates of 0.425 and 0.565 m^3/s/m were considered for the comparison as shown in **Figure** *7*. The location of the inception point shifted downstream with the increase in flow rate for both the geometry. Although there was little influence of the step height on the location of the inception point, experimental results showed that the inception point was shorter for 0.2 m steps than for 0.1 m steps.

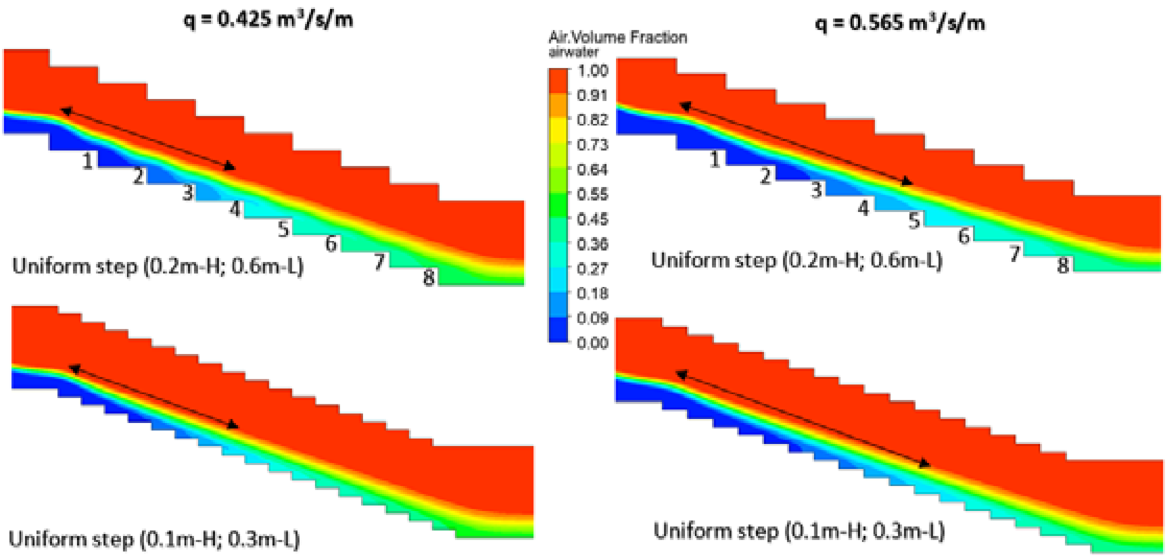

Figure 7: Influence in inception point

3.2 Turbulent Kinetic Energy (TKE)

Studying turbulent kinetic energy over the steps helps to understand the level of vigorous mixing over the steps. The generated higher TKE helps to reduce the directional flow velocity over the steps of the spillway. The influence of different adopted geometrical steps was tested with the flow of 0.565 m^3/s/m. The turbulent kinetic energy per unit mass in the form of fluctuating root mean square velocities is expressed as follows:

$$\boldsymbol{TKE = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)} \quad \textbf{(3)}$$

Where TKE is the turbulent kinetic energy per unit mass (m^2/s^2),
$\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$ are the fluctuating mean square velocities

The higher TKE indicated the vigorous mixing of water which illustrates the higher rate of energy dissipation as shown in **Figure *8***. The higher TKE of 1.42 m^2/s^2 was observed for larger steps of 0.2 m height due to well mixing of flow over the steps. The results show a higher rate of energy dissipation for the larger steps than the smaller steps.

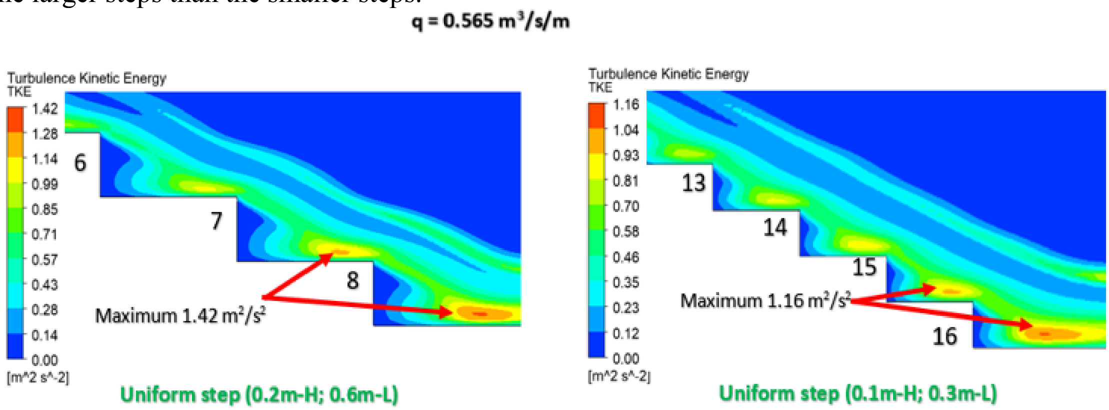

Figure 8: TKE for a flow rate of 0.565 m^3/s/m

3.3 Energy dissipation

The energy dissipation efficiency ($\frac{\Delta H}{H_0}$) and residual head (H_1) were plotted against the different specific discharges over the two adopted different geometries as presented in **Figure 9**. The adopted energy relation for evaluating the hydraulic parameter has been illustrated in **Figure *10***.

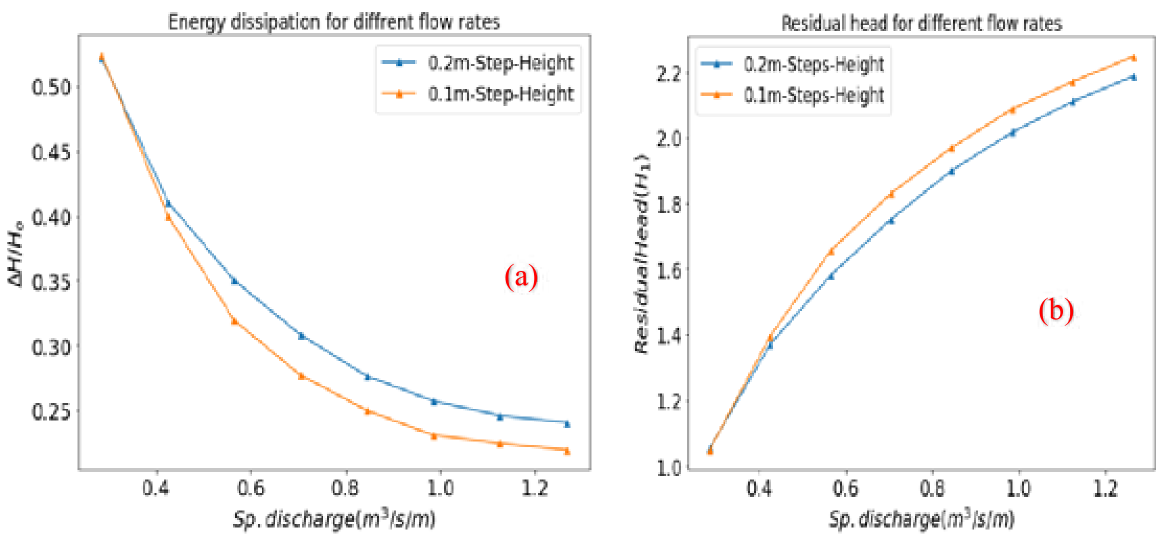

Figure 9: Energy dissipation efficiency (a) and Residual head (b)

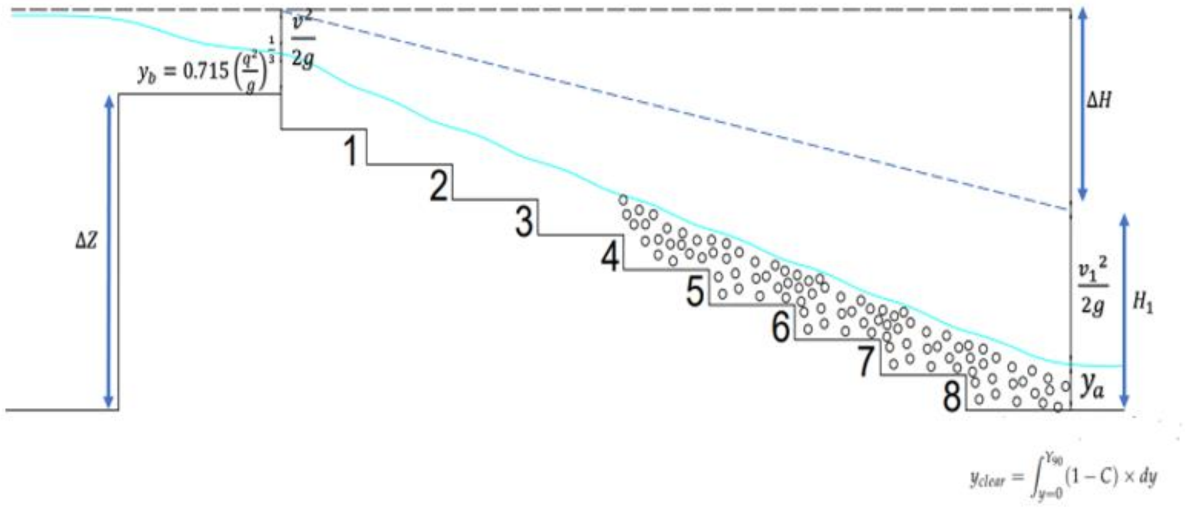

Figure 10: Adopted energy relation

The results indicate that steps with a height of 0.2 meters dissipate energy more efficiently than those with a height of 0.1 meters, especially at higher flow rates. This suggests that increasing the number of steps with a smaller roughness height decreases energy dissipation efficiency during high-flow events. However, for low flow rates, increasing the number of roughness elements does not significantly impact the energy dissipation rate.

Additionally, the plot of the residual head (H_1) for various flow rates shows that the residual head is higher for the 0.1-meter steps, indicating lower head loss (ΔH) and consequently reduced energy dissipation efficiency at high flow rates. For low flow rates, the residual head (H_1) remains relatively similar regardless of step height.

4 Conclusions

The following conclusions are drawn from the study:

- The mixture dispersed multiphase model was found to be suitable for highly disturbed flow over the steps of the spillway rather than the VOF-sharp interface model as it was unable to represent air-water mixed multiphase flow.

- The length of the inception point was found to be highly influenced by the flow rate than the adopted geometries. The length of the inception point was found to increase with the higher flow rate indicating the risk of cavitation for a higher flow rate due to the shorter non-aerated region.

- Overall, higher turbulent kinetic energy (TKE) was observed over the steps of 0.2m-H step height spillway implying higher energy loss due to vigorous mixing of flow. The design of 0.2m H steps was found to be a safe design for a higher flow rate in case of extreme events.

- The energy dissipation rate was found to be higher for the 0.2m-H stepped spillway rather than the 0.1m-H steps as a result of higher reduction of downstream flow velocity. However, for the low flow rate, the energy dissipation efficiency was found to be similar irrespective of the step height or roughness.

5 References

Boes, R. M., & Hager, W. H. (2003). Two-phase flow characteristics of stepped spillways. Journal of hydraulic engineering, 129(9), 661-670.

Baylar, A., Emiroglu, M. E., & Bagatur, T. (2006). An experimental investigation of aeration performance in stepped spillways. Water and Environment Journal, 20(1), 35-42.
Chanson, H. (1996)Air bubble entrainment in free-surface turbulent shear flows; Elsevier

Chanson, H. (2001). Hydraulic design of stepped spillways and downstream energy dissipators. Dam Engineering, 11(4), 205-242.

Dastgheib, A., Niksokhan, M. H., & Nowroozpour, A. R. (2012). Comparing of flow pattern and energy dissipation over different forms of stepped spillway. In World Environmental and Water Resources Congress 2012: Crossing Boundaries (pp. 1246-1259).

Fluent, A. N. S. Y. S. (2023). Ansys fluent theory guide. Ansys Inc., USA, 15317, 724-746.

Gonzalez, C. A., & Chanson, H. (2004). Scale effects in moderate slope stepped spillways. Experimental studies in air-water flows.

Jahad, U. A., A. Alabas, M., Mahmoud, A. S., Al-Ameri, R., & Das, S. (2024). The effect of the compound slope spillway on air entrainment and total kinetic energy using computational fluid dynamics. Water Practice & Technology, wpt2024036.

Jahad, U. A., Chabuk, A., Al-Ameri, R., Majdi, H. S., Majdi, A., Al-Ansari, N., & Abed, S. A. (2024). Flow characteristics and energy dissipation over stepped spillway with various step geometries: case study (steps with curve end sill). Applied Water Science, 14(3), 60.

Koskinas, A., Tegos, A., Tsira, P., Dimitriadis, P., Iliopoulou, T., Papanicolaou, P. & Williamson, T. (2019). Insights into the Oroville Dam 2017 spillway incident. Geosciences, 9(1), 37.

Li, S., Zhang, J., & Xu, W. (2018). Numerical investigation of air–water flow properties over steep flat and pooled stepped spillways. Journal of Hydraulic Research, 56(1), 1-14.

Pandey BR, K C MR, Crookston B, Zenz G.(2024) Numerical Investigation of Different Stepped Spillway Geometries over a Mild Slope for Safe Operation Using Multi-Phase Model. Water. 2024; 16(11):1635.

Pfister, M., & Hager, W. H. (2011). Self-entrainment of air on stepped spillways. International Journal of Multiphase Flow, 37(2), 99-107.

Saqib, N. U., Akbar, M., Huali, P., & Guoqiang, O. (2022). Numerical investigation of pressure profiles and energy dissipation across the stepped spillway having curved treads using FLOW 3D. Arabian Journal of Geosciences, 15(15), 1363.