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Assessing Spillway Modifications by Detached Eddy Simulation Turbulence Model

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Abstract Spillway associated with flip bucket structure is a famous way to evacuate the floods at dams and dissipate the flood destructive energy in order to protect the dam structure. Several spillways suffered from damages where most affected zones were located downstream the flip bucket along the flow path towards the plunge pool. Poor geometrical design is a very important main reason of the damages occurring at the downstream of the spillway. It mainly occurred when the water jet failed to achieve safe impingement location. This study proposes solutions to damages that occurred in an existing dam. These proposed solutions were tested through numerical investigations of the existing and modified spillway configuration. This investigation was originated with the aspiration of decreasing the damage of real Spillway. From the literature, previous experimental results of spillway modelling were extracted and analyzed. The results were replicated numerically by ANSYS FLUENT software. The experimental results were contrasted against the simulated results. The contrast reflected that DES results are reasonably applicable. Confident with its results, it was applied to real spillway (Base case) and results were obtained. Firstly, the existing conditions were simulated to ensure that the model mimic the existing conditions accurately. Secondly, several modifications to the existing conditions were introduced to the model and then simulated to define the most applicable solution. Detached eddy simulation is used for accurately simulation of the flow physical model. The criteria of the modification properties are developed in the way of avoiding the existing erosion problem.

Keywords Spillway Damage, Spillway Modification, Flip Bucket

1. Introduction

a) Introduction and Background

Spillways protect dams against failure by controlling the flow rate during floods. They are multi-functional structures (i.e. controlling floods, reducing water levels, releasing surplus water and maintaining water quality),. Their type depends on several factors (i.e. geological condition, topographical circumstances, dam storage, capacity, hydraulic so as hydrological settings, construction type and economic condition).

A spillway encompasses four (4) components (i.e. control structure, station structure, channel, and entrance and outlet channels). Spillways regulate the reservoir reaches its maximum designed level. The regulating devices might be sills, pipes, orifice and wire. Spillways convert water to flow through a channel (i.e. chute or waterway) in order to flow over the streambed below the dam. This surplus water is conveyed to the downstream (D.S.), which might induce serious scour holes in the channel bed. Accordingly, energy dissipater system should be supplied at the spillway toe to reduce the erosion by dissipating the kinetic energy in the flow.

b) Literature Review

Flip bucket spillway structure evacuates the flood water from the dam reservoir and dissipates the energy of the flood water downstream of the spillway.

The flip bucket spillway modeling was investigated by several researchers. These studies considered both experimental and numerical modelings. Early, a study for understanding the damage of spillway of the Karnafuli hydroelectric project was performed where the pressure variations within stilling basins were modeled [1]. The study concentrated on the effect of fluctuating pressure that caused uplift of the chute slab. The distribution pressure over the spillway crest and the velocity profile affected by roughness was investigated [4]. Computational Fluid Dynamics (CFD) model using FLOW-3D software was applied. The results highlighted that the roughness height trivially affected the pressure over the crest.

The Wivenhoe Dam spillway in Australia was studied [7]. Due to floods in 2011, it was observed that erosion rocks with huge size up to 1200 tons from the plunge pool were a real problem. This case highlighted the harsh hydraulic conditions effect corresponding to highly ventilated plunging jets. Three information sources were used, physical model, the prototype model and CFD numerical model, to simulate three cases (pre-flood conditions, post-flood conditions and finally removal of the rock mound to elevation 30 m). Results showed that high air suction with turbulent shear flow caused amplification of cracks.

The aerator role was studied for preventing cavitation damages in high velocity spillway [9]. Results concluded that at the chute's middle part, larger vent openings in large-width aerators were preferable.

Cavitation study over spillway using FLOW-3D software was assessed along spillway flip bucket of the Balaroud dam [9]. Cavitation index results were calculated and used in assessing criteria of cavitation.

The effect of roughness height of the chute spillway's bed on the cavitation index was investigated experimentally and numerically [6]. Results signified that minimum cavitation index ranged between 0.2471 and 0.2906 for the roughness heights 1 to 2.5 mm, respectively.

High velocities for high head spillways were investigated to cause damage to spillways [8] through analyzing of Shahid Abbaspour dam in Khuzestan. The remedial measures were proposed, where the consequences of designing spillways of high velocities were demonstrated.

Cavitation damage in a spillway was numerically investigated [14], where the damage occurred at the downstream steps. A concrete wedge was designed and proposed as a solution to reduce the damage.

An investigation of a spillway damage in 2107 in California, during a rainstorm was presented [3]. The study identified modifications by placing fill all over the floodway easement.

The depositions of suspended particles resulting from erosion of spillway were assessed [15]. This case was simulated by the finite volume method (FVM), where the multiphase volume of fluid (VOF) model was selected to track the flow of water through the stream, while the discrete phase model (DPM) was selected for the movement of suspended sediment particles. The simulation results showed a great agreement with the experiment, with an acceptable difference less than 4.89%.

Also, the stability of the dam affected by the local scour on the downstream was investigated [5]. In this study, a new idea was implemented by using the geocell method that based on soil reinforcement using cell confinement system. The results showed that the percentage of erosion decreased to 40.63%.

In preparation of defining and numerically testing solutions to damages occurring at and downstream of an existing flip bucket spillway, the behavior of most reliable turbulence model in simulating ogee spillway associated with flip bucket was assessed [10, 11]. Previous experimental cases were examined numerically by applying different turbulent models using ANSYS FLUENT software. Spillway and flip bucket were separately examined for different experimental cases. Based on an analogy between the numerical and experimental results, the study encouraged the implementation of detached eddy simulation model (DES) in simulating that type of flow and subsequently its application herein in assessing the solution to the existing flip bucket spillway.

The aim of this study is to test possible solutions to minimize damages occurring downstream of the ogee spillway associated with flip bucket.

c) Research Methodology

Based on the set objectives, a research methodology was planned to encompass 3 investigations. They are elaborated, as follows:

- During the Theoretical Investigation, literature in the field of spillways, turbulence models and experimental work will be presented.
- All through the Numerical-analytical investigation, the available so as the implemented model (DES) will be presented and analyzed. In addition, the simulations of 2-D spillway (base case) will be simulated; presented on graphs; analyzed and discussed. In addition, modifications will be proposed; simulated and analyzed.
- The Inferential Investigation, conclusions will be deduced.

2. Description of Case Study

An existing spillway-flip bucket system located on the left abutment of an existing dam suffers from damages downstream of the flip bucket. The existing spillway-flip bucket system consisted of the following:

a) Two span ogee spillways each is 19.5m span.
b) The ogee spillway is followed by a chute with slope 9º to the horizontal.
c) Flip bucket with radius of curvature of around 30 m and exit angle 20º follows the chute. The flip bucket is some 45 m higher than the riverbed.
d) 5 steps from the flip bucket edge.

The flood flows passing over the spillway resulted in damages to the steps downstream of the flip bucket in addition to the reinforced concrete slab located on the bed of the river.

Figure 1 presents the damages downstream of the flip bucket, while Figure 2 presents the cross-section of the spillway system.

Figure 1. Corrosion damage at stepped ramp

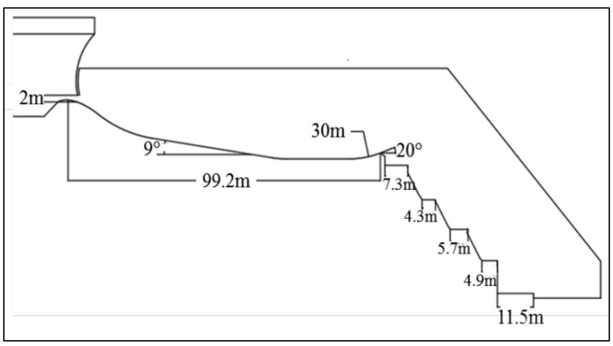


Figure 2. Spillway longitudinal section

3. Base Case Analysis

The existing spillway – flip bucket system was modeled using ANSIS FLUENT software. The model was based on the following:

1) Actual spillway flip bucket 2D section. Figure 2 presents the model geometry.
2) Gates partial opening of 2.0 m.
3) Use of Detached Eddy Simulation (DES) as the turbulent model.

The numerical process proceeded as follows:

1) Preparation of the model geometry and grid.
2) Checking of the model geometry and mesh devlopment.
3) Definition of the boundary conditions. The boundary conditions used were as follows:
   a) Upstream boundary condition was defined as inlet pressure by a constant water height.
   b) Downstream boundary condition was defined as outlet pressure.
   c) Bottom boundary is defined as wall roughness effect.
   d) Top boundary was defined as inlet pressure pressure.
4) Defining the type of flow as multi-phase flow where volume of Fluid (VOF) method was used.
5) Definition of initial conditions was based on starting flow by the action of the constant head of the reservoir.
6) The numerical simulation was carried out and the results were compared to field data. The available field data are pictures of the flow passing over the flip bucket and some reporting of the damges occurred. These pictures show the flow passing over the spillway and the location of impinging of the flip bucket jet, sample of these pictures are showin in Figure 3. which shows that the jet hit step 4.

Figure 3. Picture of the flow passing over the spillway-flip bucket system

The numerical results show that the flow passing over the flip bucket impinges at step number 4 as presented in Figure 4. This simulations results show a good agreement with the field data.

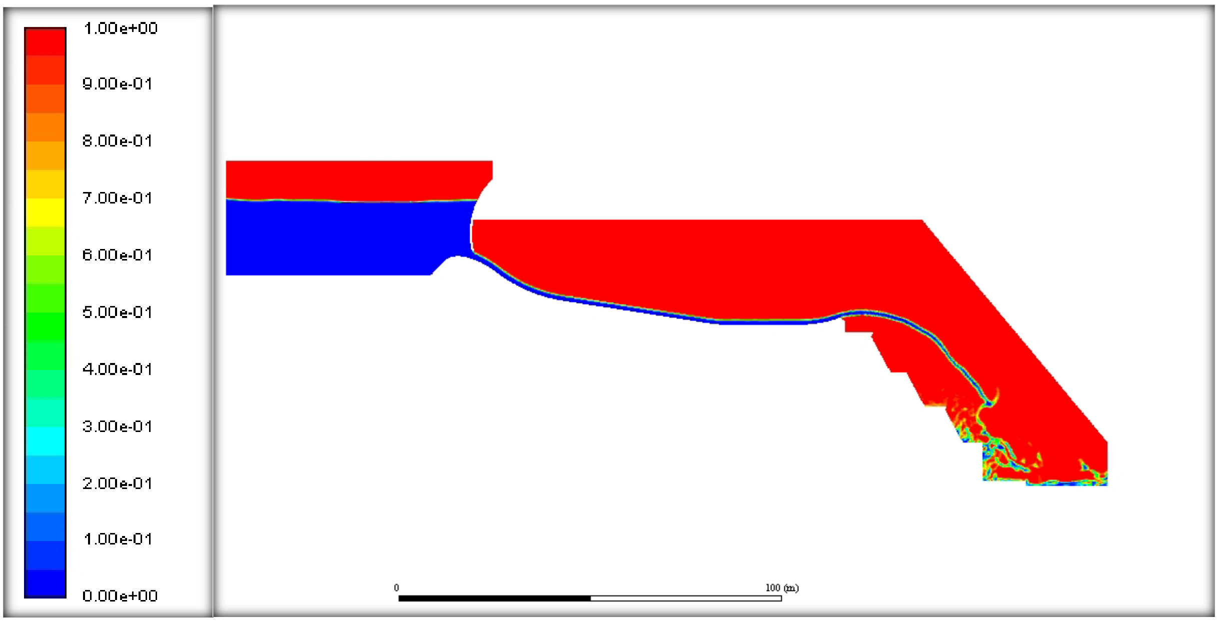
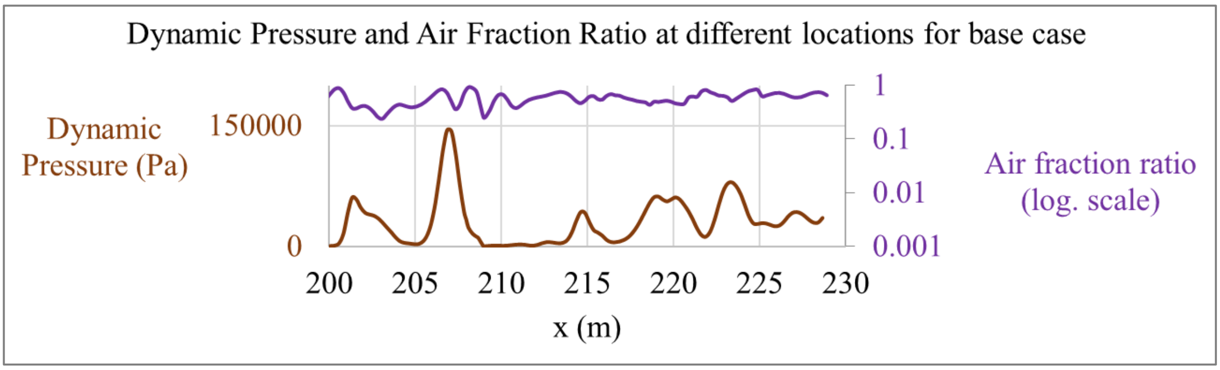


Figure 4. Base case simulaton results.



Close to x=205 the air at distance

Figure 5. Dynamic Pressure and Air Fraction Ratio at different locations for base case

The analysis of the flow passing over the spillway system shows the following:

(1) The velocity at the chute distance is in the range of 22 m/s. This velocity is relatively small where it does not help the jet to pass to the downstream of the flip bucket base.

(2) It appears also that the relatively small velocity is due to the flat slope of the chute specially close to the flipbucket section.

(3) The jet passing the flip bucket shows a very small rise which results in short distance of impinging. This could be due to the small flip bucket angle.

(4) High Air fraction ratio excessed 0.7 (70%) was observed at at the location of the impangiment area of step 4 and this ratio was increaseed in downstream zone as shown in figure 5. The results refelected high air entray process which describes the large white zones of the flow jet shown in figure 3.

(5) The dynamic pressure distribution in figure 5. was highly consistent with the air fraction ratio in obivious inverse relations. The location of high dynamic pressure corresponding to low air fraction values was used to precisely define the impingment location and the trajectory length. The impingiment location can be estimated at x-distance about 205 m with high dynamic pressure close to 150,000 Pa and low air fraction of around 0.15.

4. Proposed Solutions

Based on the analysis of the base case, it appears that we have several parameters to change to achieve better performance of the flip bucket. These parameters are the slope of the chute, the flip bucket radius of curvature, the flip bucket angle and the shape of the steps downstream of the flip bucket.

Changing the Slope of the Chute:

Changing the slope of the chute is an apparent solution as increasing the slope will result in increased velocity and as such will increase the jet distance downstream. However, increasing the slope of the chute will also entail the following:

- Excessive cut in rock
- High risk at the downstream end as the cut will be required at the existing steps.
- High walls and increased quantities of slope stabilization.
- High cost of implementation

Based on this analysis, the changing of the chute slope was discarded and no change in chute slopes was considered in this analysis.

Radius of Curvature:

The bucket radius was suggested to be 4 times as much as the flow maximum depth [2, 10], which provides a long sufficient inclination for water to turn before leaving the bucket and assures the thrown jet to fall at the downstream area. Based on this suggestion and the calculated depth of water at the flip bucket (max. depth of water equal 7 m) four values for the radius of curvature were proposed to be checked.

The values proposed are 32, 42.5, 45 and 68 which are 4.57, 6, 6.42, and 9.7 times of the water depth.

Changing the radius of curvature is practically implementable and as such these different proposed radii of curvature were considered as part of the solution.

Flip Bucket Angle:

The flip bucket angle should be within 15° to 35° [2, 10], as angles less than 15° do not provide enough lift to clear bucket structure and it is more than enough for angles above 35°. Based on this suggestion different flip bucket angles were proposed. These angles were 17°, 22°, 30° and 45°.

Shape of Steps:

Having a sharper slope of the steps could be a solution as shortening the steps horizontal distance will result in having the jet hitting the bed away from the slopes. However, this work will also entail the following:

- Excessive cut in rock
- High risk at the downstream end as the rock condition is not good at the toe of the flip bucket.
- Increased quantities of slope stabilization.
- High cost of implementation

Based on this analysis the changing of the shape of the steps was discarded and no change in steps shape was considered in this analysis.

Based on the above analysis four modified sections were proposed as presented in Table 1 and Figure 6.

Table 1. The original and proposed modified sections

Case Number	Case Name	Slope	Exit angle (α_j)	R (radius) m
0 (Original)	OC	9°	20°	30
1 (Modified)	A	9°	17°	68
2 (Modified)	B	9°	22°	42.5
3 (Modified)	C	9°	30°	45
4 (Modified)	D	9°	45°	32

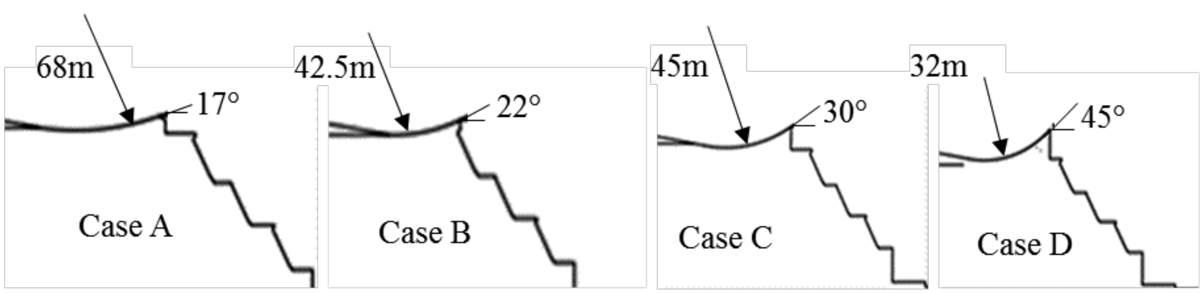


Figure 6. Proposed modified sections

5. Results of Proposed Solutions

The different proposed modifications were modeled using the same procedure as the base case. Different parameters were checked to define the performance of each modification. The parameters tested were as follows:

(1) Trajectory distance which was calculated using the flow profile and the dynamic pressure results. Figure 7 presents the flow profile while Figure 8 presents the dynamic pressure results for the four cases. Case B shows that the trajectory is far from the spillway system toe while other cases show shorter trajectory distance. Table 2 presents the calculated trajectory distance measured from the flip bucket lip.

(2) Figure 9 presents the velocity profile for the four cases. Cases B, C and D show the high velocities to be located away from the toe of the spillway system. Table 2 presents the velocity at the flip bucket tip and the corresponding trajectory length in each case.

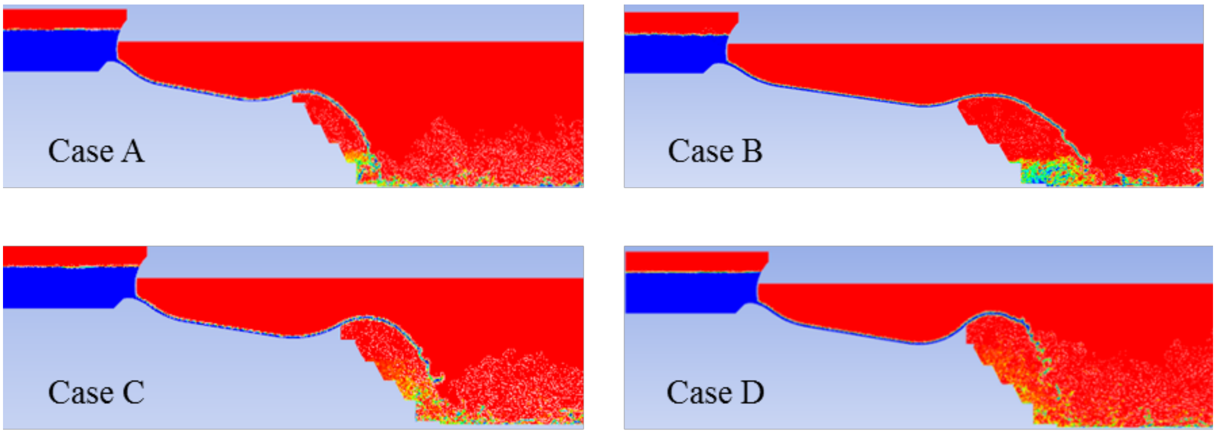


Figure 7. Flow profile

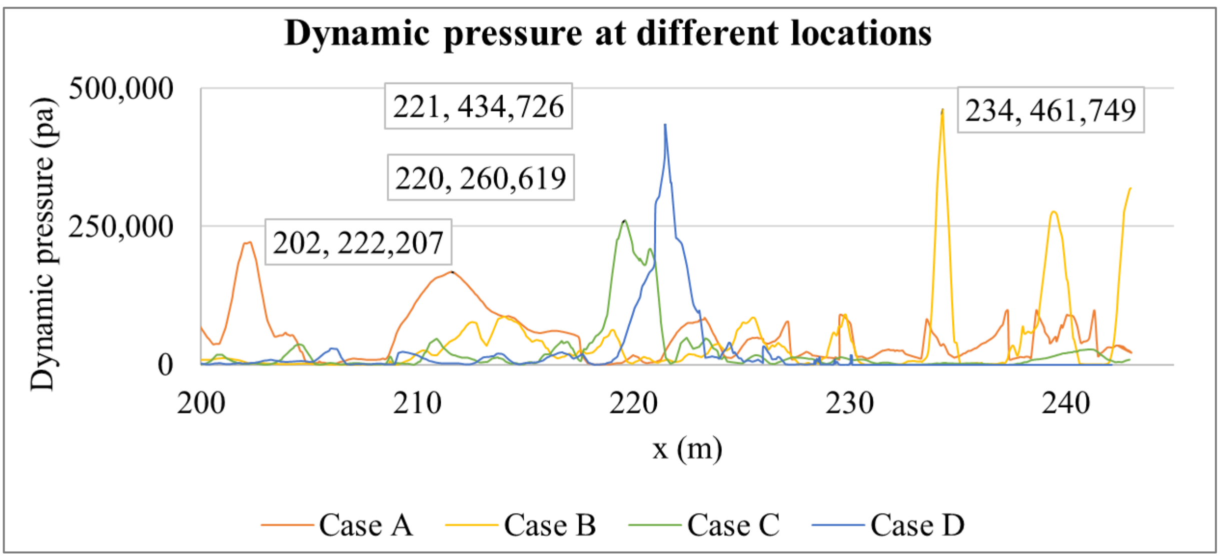


Figure 8. Dynamic pressure at different locations

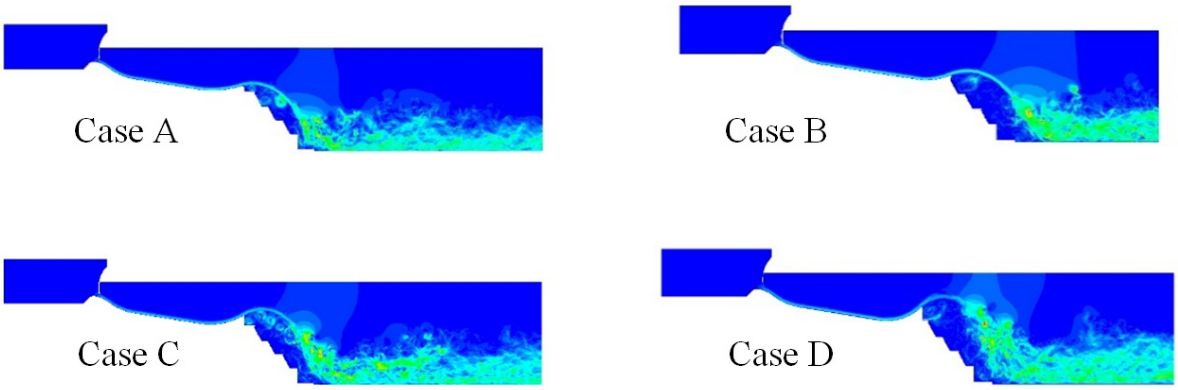


Figure 9. Velocity profile over spillway system

Table 2. The results of jet velocity and trajectory distance at the impact location

Modification Case	Jet velocity (m/s)	Trajectory distance (m)	Location (Inside/Outside) of steps zone
A (angle 17)	23.45	51	Inside steps zone
B (angle 22)	24.14	65.9	Outside steps zone
C (angle 30)	22.3	59.5	Outside steps zone
D (angle 45)	21.7	56.5	Outside steps zone

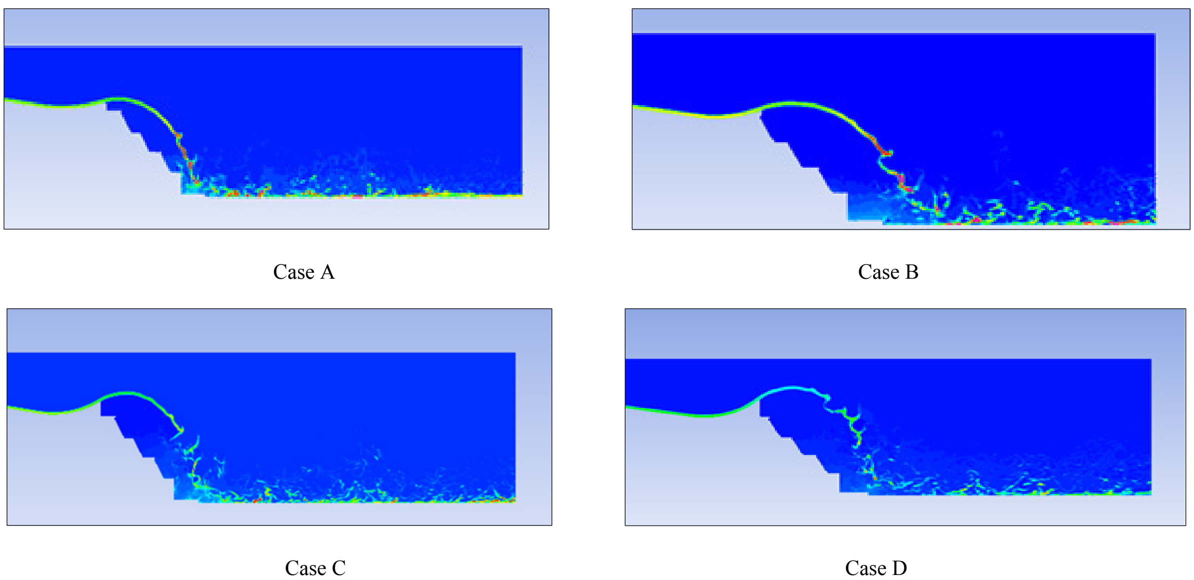


Figure 10. Total pressure

(1) The total pressure on the spillway system is presented in Figure 10. The high values of the total pressure (red color zone) for cases B, C and D are away from the spillway system toe. Cases C and D are within 10m downstream of the steps toe while Case B shows distances more than 15 to 20 meters downstream.

(2) The turbulent intensity is presented in Figure 11. Case B shows that the turbulence is far from the toe of the spillway while all other cases show turbulent conditions close to the toe with case A the worst.

(3) The value of volume of fraction (air concentration) is presented in Figure 12. The results show that the air concentration decreases at the location of impact where the air concentration decreases to close to 20%. The location of the lowest air concentration represents the jet impact location. The results show that the lowest air concentration in case B is located away from the toe and a distance of almost 66m.

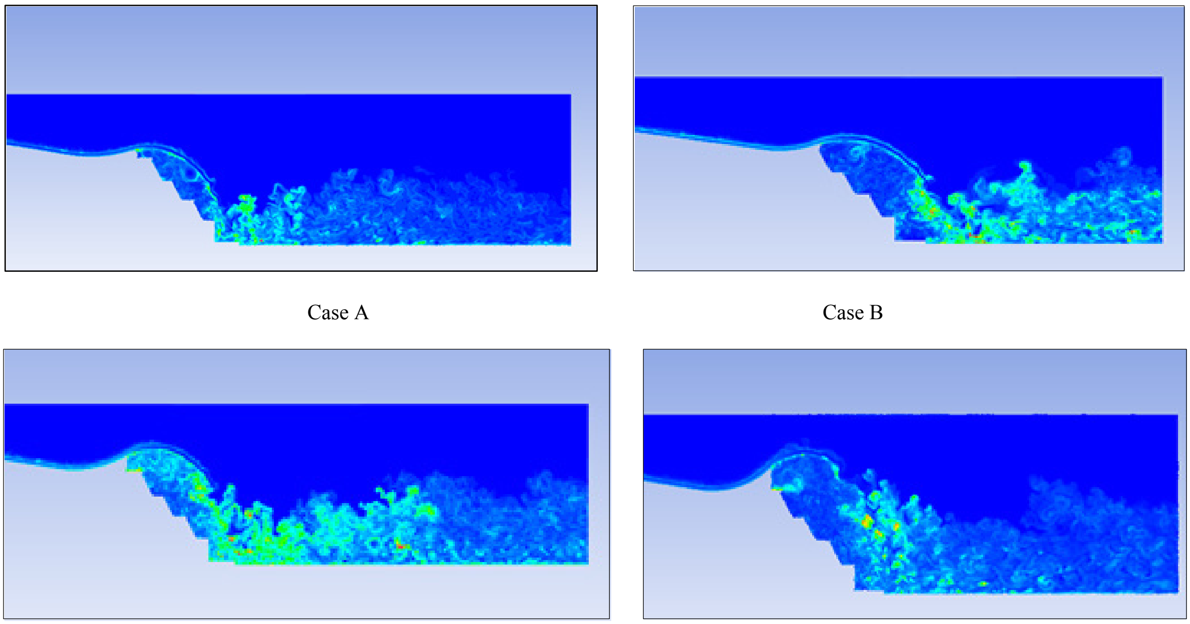


Figure 11. Turbulent intensity for jet flow

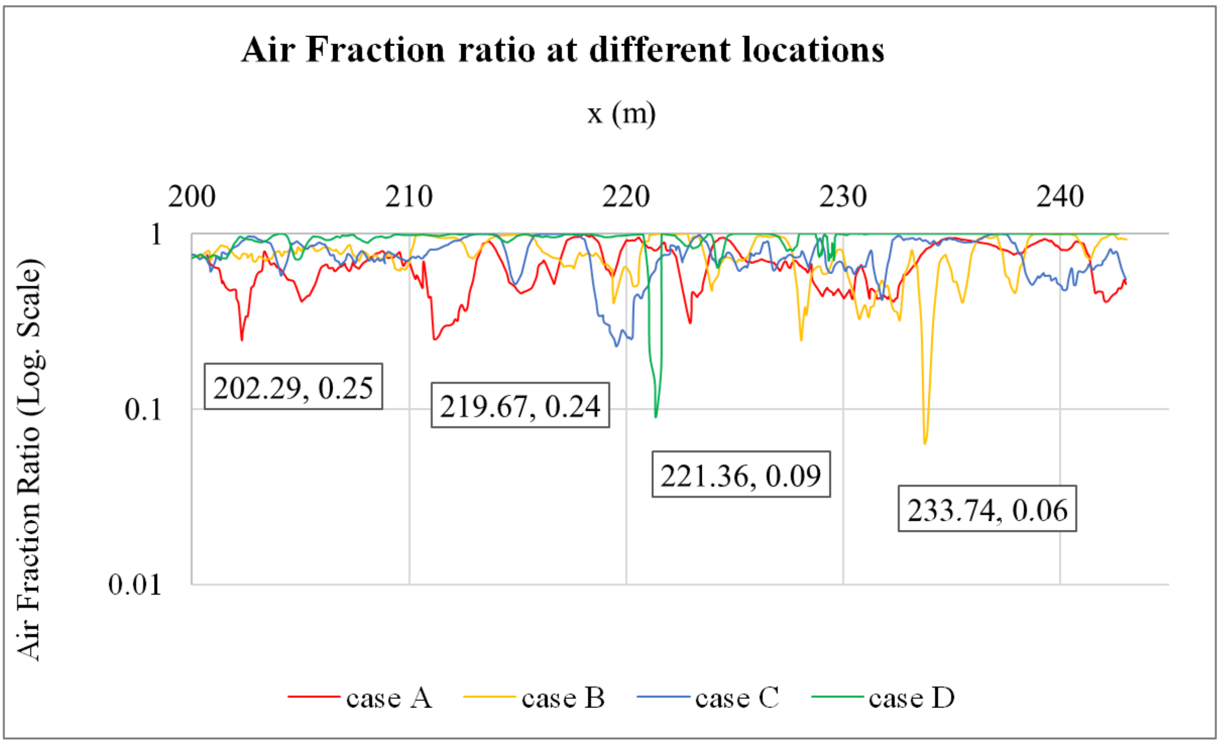


Figure 12. Air fraction ratio

The results show that case B is a better solution as it ensures that the spillway toe is away from the impact of the flow jet.

6. Conclusions

The study performed an analyzed problem in an ogee spillway-flip bucket system of an existing dam. The problems were observed and reasons of the problems were defined using numerical modeling. Solutions were proposed and the most applicable solutions were selected. The conclusions can be summarized as follows:

(1) Numerical modeling using ANSIS FLUENT software with considering Detached Eddy Simulation (DES) as

the turbulent model proves to simulate the actual conditions on site.

(2) Radius of curvature of the flip bucket has high effect on the flip bucket performance.

(3) Take-off angle of the jet of flow has an additional dependent effect conjugated with the radius in controlling the jet flow properties.

(4) Dynamic pressure and air fraction have an important role in defining the point of impact of the spillway jet.

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