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Flow Over the Spillway of AlAdhiam Dam Under Gated Condition

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ABSTRACT

The Al Adhaim Dam is located 133 kilometers northeast of Baghdad. It is a multipurpose dam and joints the Iraqi dam system in 2000. It has a storage capacity of 1.5 billion m^3. The dam has an ogee spillway with a length of 562 m, a crest level of 131.5 m.a.m.s.l. and a maximum discharge capacity of 1150 m^3/s at its maximum storage height of 143 m.a.m.s.l. This research aimed to investigate the hydrodynamics performance of the spillway and the stilling basin of AlAdhiam Dam by using numerical simulation models under gated situations. It was suggested to modify the dam capacity by increasing the dam's storage capacity by installing gates on the crest of the dam spillway. The FLUENT program was used to simulate the flow over the spillway. The free surface was calculated using the volume of fluid (VOF) method. To deal with turbulence, the SST k-ω turbulence model was used. The study showed that the spillway is capable of carrying the designed flood discharge and the modified conditions with negative pressure behind the gate and at some points along the spillway. Hydraulic jumps occur at various distances throughout the plunge pool depending on the incoming velocity in the flip bucket.

Keywords: Ansys Fluent, Numerical CFD model, SST k-ω method, Gated condition, Spillway.

جريان المياه فوق المسيل المائي لسد العظيم في حالة وجود بوابات

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الخلاصة

يقع سد العظيم على بعد 133 كيلومترا شمال شرقي بغداد. بدأ تشغيله في عام 2000. وهو سد متعدد الأغراض. تصل سعته التخزينية إلى 1.5 مليار م^3. تم استخدام مسيل أوجي للسيطرة على تدفق الفيضان بطول 562 م وكان مستوى القمة 131.5

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م فوق مستوى سطح البحر وأن اقصى تصريف تصميمي عند 1150 م^3/ ث وأقصى ارتفاع للفيضان 143 م فوق مستوى سطح البحر. تهدف الدراسة إلى التعرف على الديناميكية للمسيل المائي والاداء أحواض التسكين لسد العظيم باستخدام نماذج المحاكاة العددية عند الحالة المبوبة . تم اقتراح زيادة السعة التخزينية للسد عن طريق تركيب بوابات على قمة مجرى السد. تم استخدام برنامج FLUENT لنمذجة التدفق فوق مجرى المسيل المائي. تم حساب السطح الحر باستخدام طريقة حجم السائل (VOF). للتعامل مع الاضطراب ، تم استخدام نموذج SST k−ω المضطرب. أوضحت الدراسة أن المجرى قادر على حمل تصريف الفيضان التصميمي بضغط سلبي يحدث خلف البوابة وفي بعض النقاط على طول المسيل المائي. اعتمادًا على السرعة الداخلة الى flip bucket, تحدث القفزات الهيدروليكية على مسافات مختلفة خلال حوض التسكين.

الكلمات الرئيسية: المسيل المائي,حالة البوابات,النموذج العددي,ديناميكية الموائع الحسابية, برنامج FLUENT.

1. INTRODUCTION

The Al Adhaim Dam was built on the Al Adhaim River t 133 km north of Baghdad City. It is a multifunctional dam that provides power, flood control, and water storage for irrigation and other uses. The dam body is made up of a 3800m long earth fill dam with a clay core with a height of 76.5 m and a top width of 12 m. The upstream side of the dam body is protected by concrete block riprap. The reservoir storage volume is 1.5 billion m^3 covering an area of 120 km^2. Its spillway was designed to release flood waves at a rate of 1150 m^3/s.

The Ministry of Water Resources intended to increase the dam's storage capacity by installing gates on the dam spillway to increase the water level of the dam reservoir. The performance of the spillway and the stilling basin of the dam must be investigated under this condition. A numerical simulation model can be developed by using CFD software. This software provides detailed hydrodynamics calculations of the flow over the spillway and within the Al Adhaim Dam stilling basin under the gated case.

CFD was used to simulate flow over ogee spillways by many studies and showed to be accurate as the results were compared to data acquired from physical models or field measurements. **(Daneshkhah and Vosoughifar, 2012),** investigated the effects of various turbulence models on the appropriate flow parameters over an ogee spillway. The results show that the RNG k-ε turbulence model, which was used, had significantly higher accuracy than the other models. **(Zhenweia et al., 2012)** investigated by using numerical 3D simulation of the spillway flow field using VOF method. The standard k-ε turbulence model was applied, which employed turbulent flow with high velocity in the chute. The results show that the single hole scheme is better than the two holes scheme because of the effect of the pier and the bigger deflected angle in the two holes scheme. **(Kumcu, 2016)** studied the flow over the Kavsak Dam spillway modeling as well as a comparison of experimental data with CFD analysis. FLOW-3D CFD software was used for the numerical simulation. For the turbulence model, k-ε was employed. The results of the physical model and the numerical mode were compared using discharge rating curves, velocity patterns, and pressures. It shows that the difference between the CFD and the physical models is 3.2%. **(Mohammed et al., 2017),** used the commercial CFD software to test an ogee-crested spillway at three different heights. The results revealed that the data from physical and numerical models for water surface profiles agreed well, despite some pressure differences. **(Zawawi et al., 2018)** investigated several open gates of a dam spillway. ANSYS program to create the 3D flow. Three dam spillway models were created for the simulation, with each model having a different gate opening height. The result showed that the area of the gate gap would affect the speed of the water released from the dam and the impact of the water discharge to the bottom downstream. **(Almawla et al., 2021)** used computational fluid dynamics to investigate the flow pattern of the Haditha Dam spillway. Ansys Fluent software was utilized for the numerical model. They used (VOF) model for turbulent flow and the k- ε model for multiphase flow to simulate multiphase flow. The result shows a good agreement between physical and numerical models. **(Hussain et al., 2022)** conducted a hydrological study on modifying the Adhiam Dam Spillway by installing gates in the spillway to save more water. Two gate installation options were modeled. Installing a pair of gates near the lake outlet was one option. Installing a pair of gates above the spillway crest is the second option. The study found that the obtained maximum discharges agreed with that obtained design discharges, and installing gates is a good suggestion to increase the capacity of the Adhiam Reservoir.

2. DESCRIPTION OF THE STUDY CASE

Two 6 m slice vertical gates with lip face having a 45-degree angle will be installed on 15 m of the spillway wide, the width of each gate 0.2 m, and the height of the gate is 13 m with a 2 m wide pier between them. Five gates opening to be examined between 2m and 10m opening. **Fig.1**. shows the details of the spillway and the stilling basin of AlAdhiam Dam after 2m gate opening

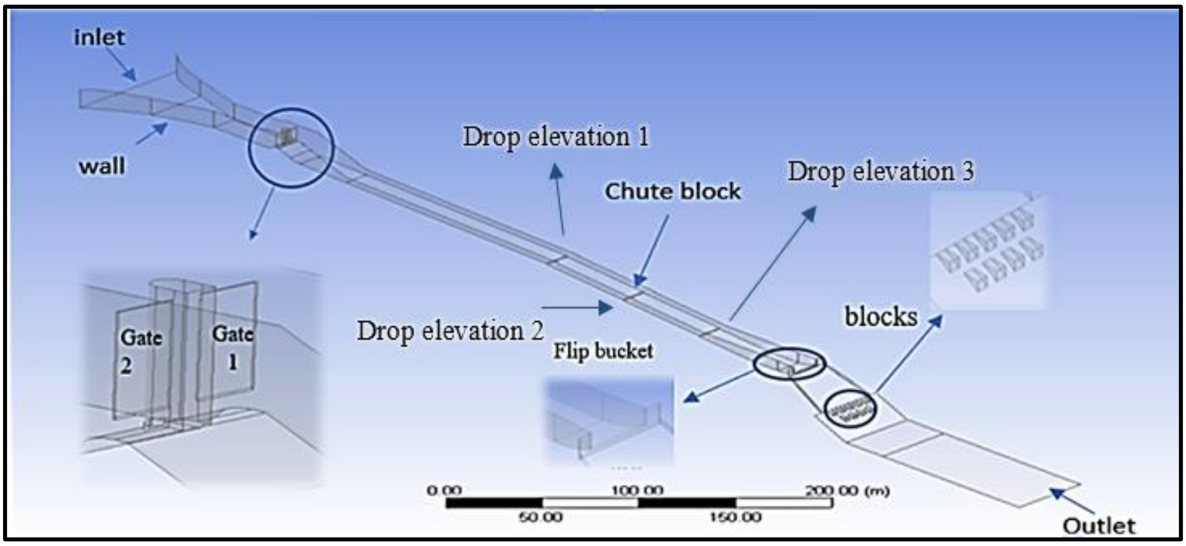


Figure1. The details of the spillway and the stilling basin of AlAdhiam Dam after the gate at 2m opening.

3. THE GOVERNING EQUATIONS

FLUENT software was used to study the hydraulic performance of the free surface flow over the ogee spillway and the stilling basin of Al Adhaim Dam. The simulation model's geometry was plotted by using ANSYS Parametric Design Language, APDL. The output file of APDL is inserted through the read case of FLUENT. FLUENT is the most common and suitable software of CFD that offers a huge advanced physical model for fluid flow. The finite volume method can solve the

3D differential equations and algebraic equations. In this program, the volume of fluid (VOF) model was used to determine the free surface of the flow. **(Nichols and Hirt, 1981),** presented a model for determining the common surface of a two-phase fluid, which is useful in a variety of hydraulic issues. The equations governing the flow over the spillway are Reynolds averaged Navier Stokes. Among the governing equations are the continuity and momentum equations, as follows **(Daneshfaraz et al., 2016)**.

$$\frac{\partial u_i}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i \, \partial u_j}{\partial xj} = \frac{\partial}{\partial x_j}\tau_{ij} - \frac{1}{\rho}\frac{\partial P}{\partial x_i} + g_i \tag{2}$$

The Reynolds stresses, which operate on the fluid and apply the effects of turbulence vortices, are the parameter:

$$\tau ij = \rho \, v_i \left(\frac{\partial u_i}{\partial x} + \frac{\partial u_j}{\partial x}\right) - \frac{2}{3}\rho k \delta_{ij} \tag{3}$$

Where:

t =is time, s

u_i = the velocities in the x_i directions, m/s

ρ =is the volume-fraction-averaged density, *kg/m*^{3}

g = acceleration due to the gravity, m/s^2

v = kinematic viscosity, N.s/m^2

p= pressure, *pa*

$\delta_{ij=}$ Kronecker delta and this will be 1 if i = j and 0 otherwise.

FLUENT has various turbulent models to solve turbulent flow conditions, including Spalart-Allmaras, k-large eddy simulation (LES), Reynolds stress model (RSM), and k-ω. The usage of the SST k-ω turbulence model, a two-equation semi-empirical model, will be the focus of this research. Due to the model's simplicity, its accurate and robust formulation of the k - ω model in the near wall zone with the k-ε model free-stream independence in the far field (**ANSYS Fluent Theory Guide). T**he SST k-ω turbulence proved to give satisfactory results in both studies **(Alwan and Azzubaidi, 2021) and (Al-Sarefi and Azzubaidi, 2021).** The following equations can describe the model:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k \tag{4}$$

$$\frac{\partial}{\partial t}(\rho\omega) + \frac{\partial}{\partial x_j}(\rho\omega u_j) = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega + S_\omega \quad (5)$$

Where G_k represents the generation of turbulence kinetic energy due to mean velocity gradients.
G_ω represents the generation of ω.
Y_ω and Y_k represent the effective dissipation of ω and k due to turbulence.
S_k and S_ω are user-defined source terms.
σ_k and σ_ω are the turbulent Prandtl numbers for k and ω, respectively.
D_ω represents the cross-diffusion term.
The turbulent viscosity is computed as follows:

$$\mu_t = \frac{\rho k}{\omega} \frac{1}{\max\left[\frac{1}{\alpha^*} \frac{SF^2}{\alpha^1 \omega}\right]} \quad (6)$$

Where:
K= turbulent kinetic energy, m^2/s^2
ω = turbulent dissipation rate, m^2/s^3
μ_t = turbulent viscosity,
F= the blending function.
S =the strain rate magnitude,
In the high-Reynolds number form of the k - ω model, $\alpha*$ =1, a_1 = 0.31

4. BOUNDARY CONDITIONS

The problem is one of the most important stages of numerical flow field analysis. The CFD software provides a variety of boundary conditions that can be used to determine the domain solution. The upstream boundary is the pressure inlet. The downstream boundary is the pressure outlet which is the atmospheric pressure for both upstream and downstream sides, channel walls are the bottom boundary, and side walls and blocks are defined as nonslip walls in this study's numerical modeling of the ogee spillway. The no-slip boundary indicates that the velocity at the walls is zero, that the roughness height ks for smooth concrete is 0.5mm (**Engineering ToolBox, 2003)** and that the default roughness constant cs is 0.5.

5. ANALYSIS METHOD

Meshing is the first step in mathematical analysis after the geometry has been prepared. As shown in **Fig.2**, a tetrahedral mesh suitable for use with a 3D model was used. For all the gated conditions: the largest grid size was 8 m. A smaller mesh with a minimum size of 0.01m was used to obtain accurate results in areas where flow conditions are expected to be highly variable. The bed of the spillway has a maximum face size of 0.1 m. The total number of cells obtained is estimated to be around 3.5 million. Skewness was measured is 0.77, which is considered acceptable (**ANSYS Fluent Theory Guide).** The aspect ratio calculates how much the cell has been stretched, which is 1.16 for the minimum value.

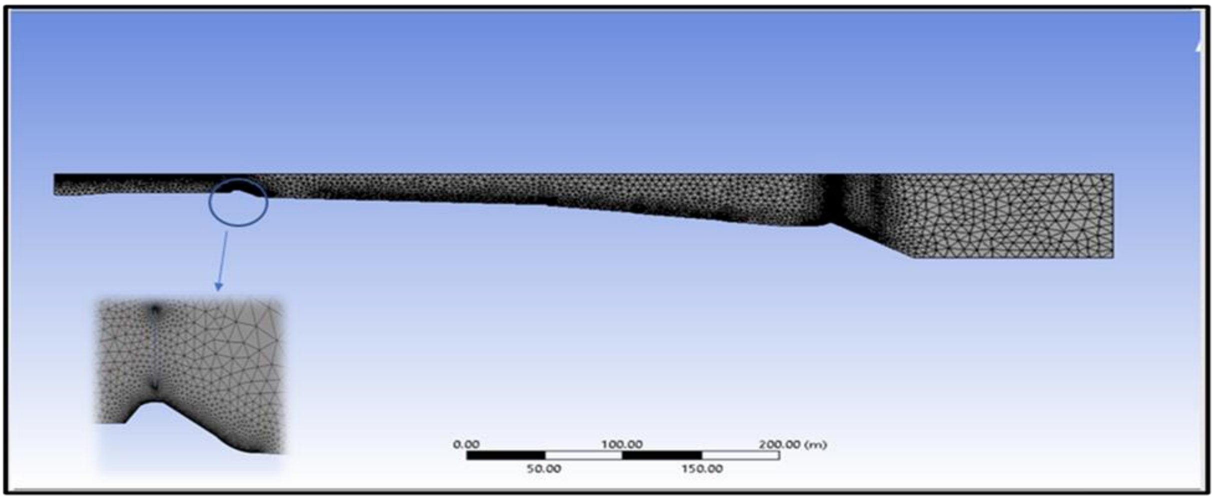


Figure 2. Meshing for the gated condition at 2 m gate opening.

The governing equations are discretized using the PRESTO pressure discretization scheme and the finite volume method. The PISO technique, which is only used for transient simulations, could be used to couple the pressure and velocity **(ANSYS Fluent Theory Guide)**. Under-relaxation factors are used to stabilize the convergence behavior of the outer nonlinear iterations in the pressure-based solver by starting arbitrary amounts of ϕ into the system of discretized equations. The under-relaxation factors, such as the pressure coefficient, k, momentum coefficient, and ω are all set to their default values of 0.3, 0.7, 0.7and 0.8, respectively. In the vast majority of cases, the default values are close to ideal. The size of the time step depended on the gated condition.

6. RESULTS AND ANALYSIS

The velocity, surface of the water level, and pressure variation over the spillway and along the stilling basin of AlAdhiam Dam were obtained under different gate openings at the maximum capacity of the spillway at 1150 m^3/s.

The rating curve shown in **Fig. 3** was obtained based on the result of runs under different conditions of the gate opening. The discharges vary from 257.32 to 1036.3 m^3/s, corresponding to the gate opening 2 and 10m, respectively.

Fig. 4 shows the variation in the location of the Hydraulic jump along the spillway of the AlAdhiam Dam and the gate opening. The Hydraulic Jump is located between 405.3 and 428.4 m from the spillway crest after the flip bucket for the gate opening of 2 and 10m, respectively.

Fig. 5 to Fig. 9 show the water volume fraction at the spillway and along the stilling basin of AlAdhiam Dam under different gate openings**.** For all cases, the water level at the inlet side of the spillway is 16.5 m above the bottom elevation of 126.5 m.a.m.s.l. The water level from the gate depends on the gate opening, ranging between 2m to 10 m. When the gate is opened, there is also a jet of water and vortices.

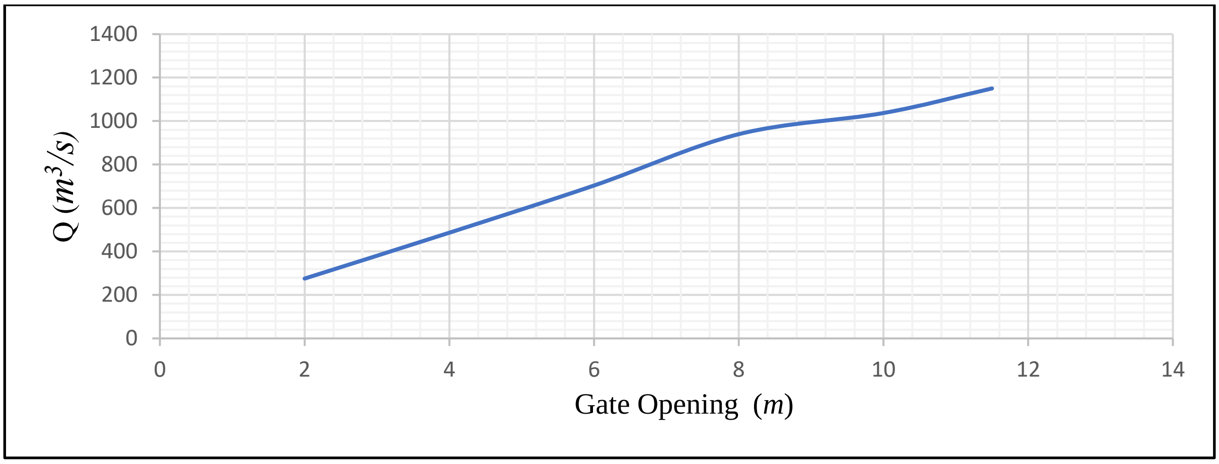


Figure 3. Rating curve between discharge and gate opening.

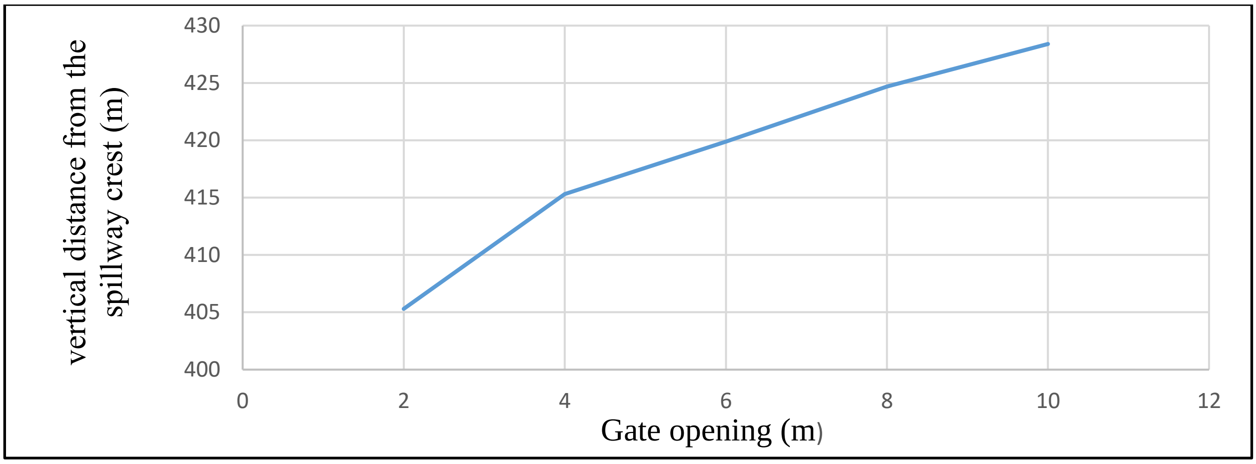


Figure 4. Location of the Hydraulic jump along the spillway of the AlAdhiam Dam.

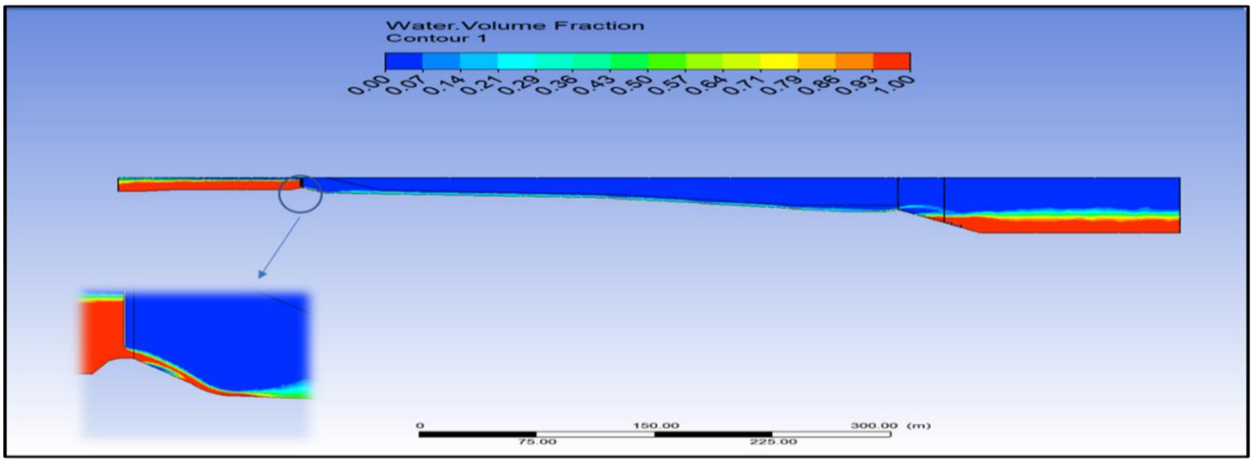


Figure 5. Water volume fraction at the spillway and the stilling basin of AlAdhiam Dam at 2m gate opening.

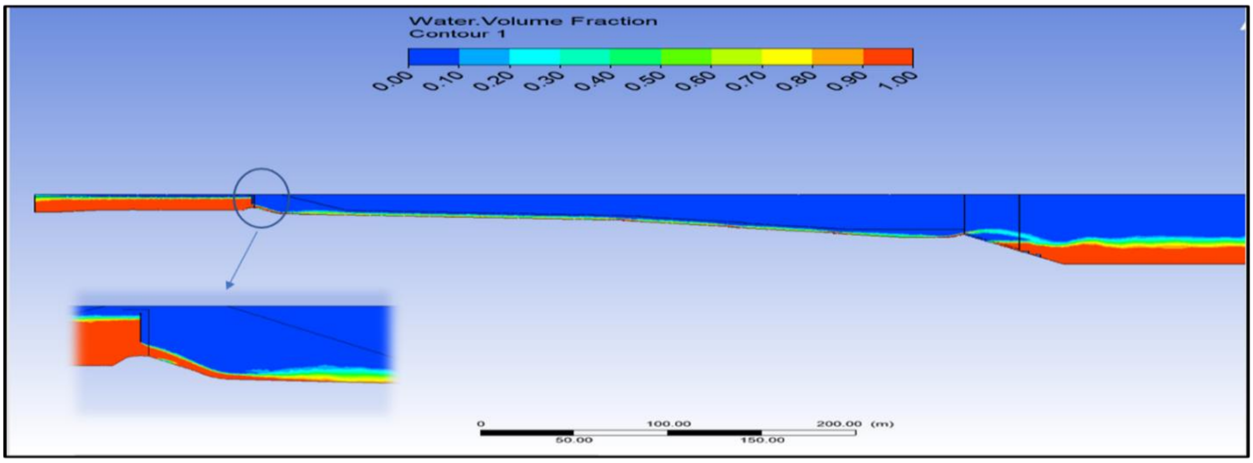


Figure 6. Water volume fraction at the spillway and the stilling basin of AlAdhiam Dam at 4m gate opening.

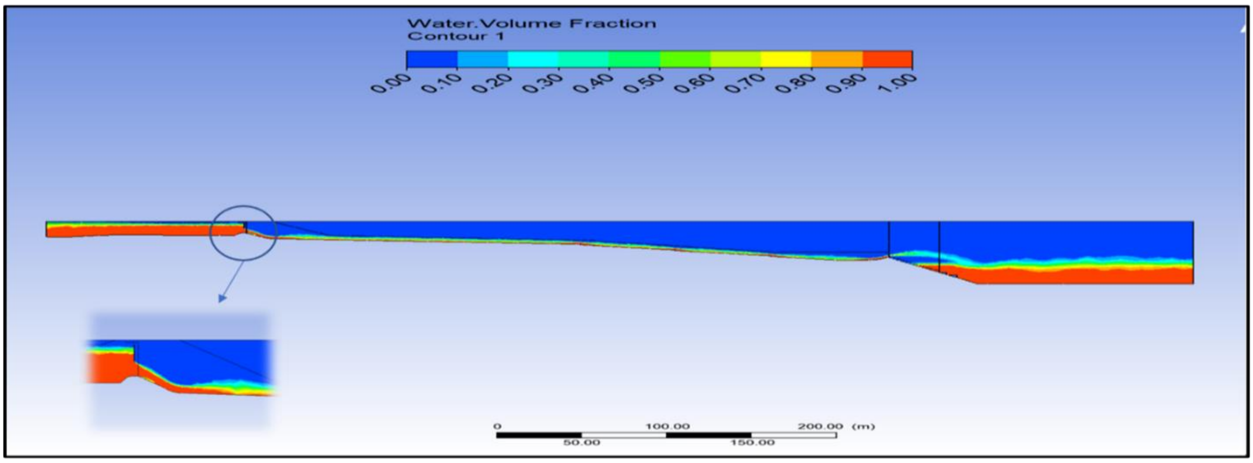


Figure 7. Water volume fraction at the spillway and the stilling basin of AlAdhiam Dam at 6m gate opening.

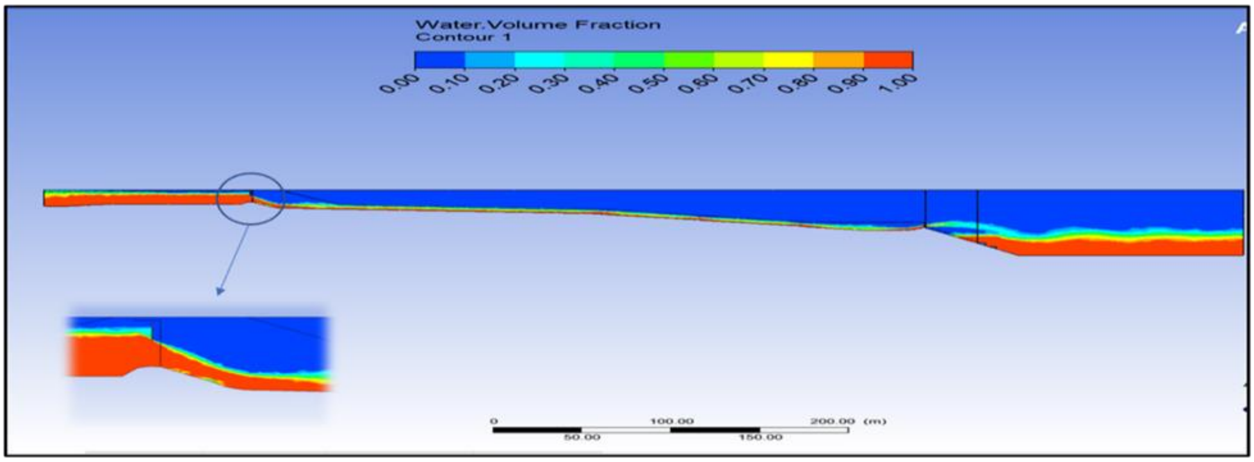


Figure 8. Water volume fraction at the spillway and the stilling basin of AlAdhiam Dam at 8m gate opening.

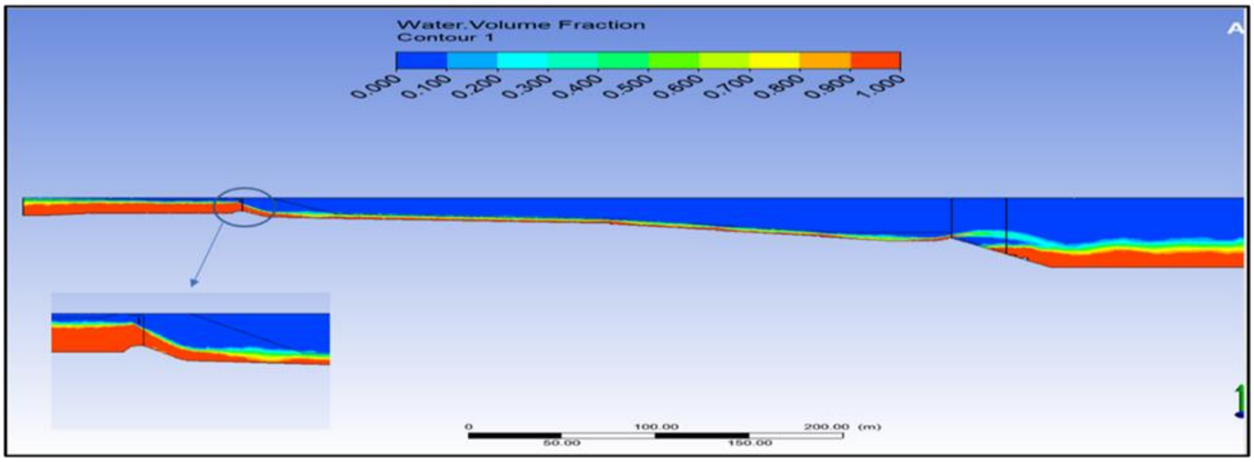


Figure 9. Water volume fraction at the spillway and the stilling basin of AlAdhiam Dam at 10m gate opening.

Fig.10 to **Fig.14** show the velocity variation along the stilling basin of Al Adhaim Dam after the opening gate. A summary of the velocity variation is presented in **Table 1**. The flow velocity at the inlet side of the spillway for all cases gated reached 1.68 *m/s*, then the velocity increased towards the spillway crest. The velocity under the gate varies from 12.86 to 14.80 m/s, corresponding to the gate opening 2 and 10m, respectively. The velocity at the flip bucket reaches its maximum value of 20.05 to 24.23 m/s, corresponding to gate openings of 2 and 10 meters, respectively.

Table 1. Different gate opening values and velocity variation

Gate opening (m)	Maximum velocity under the gate (m/s)	velocity at the in drops elevation (m/s) drop 1, drop2, drop 3	velocity at the flip bucket (m/s)
2	12.86	11.63, 8.56, 10.23	20.05
4	13.34	12.25, 11.56, 12	21.63
6	14.24	13.36, 12.37, 12.32	23.37
8	14.79	13.47, 12.54, 12.48	23.71
10	14.80	14.09, 12.88, 12.76	24.23

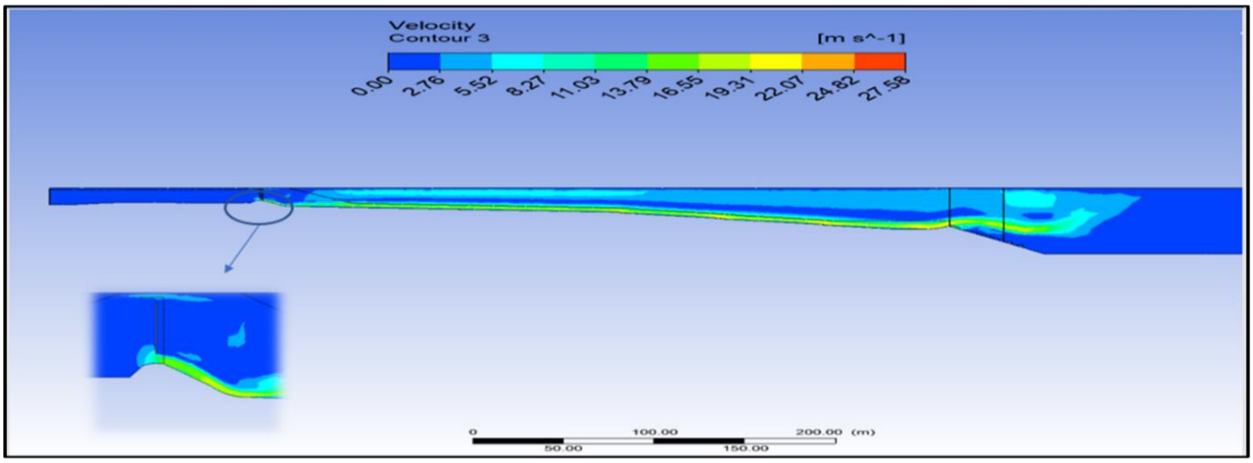


Figure 10. Velocity variation over the spillway and along the stilling basin of AlAdhiam Dam at 2m gate opening.

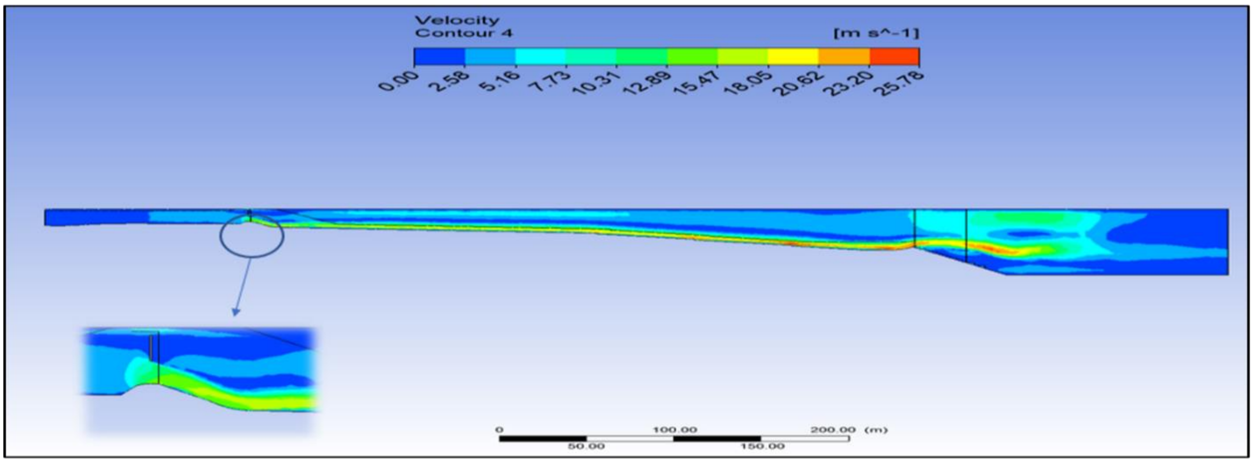


Figure 11. Velocity variation over the spillway and along the stilling basin of AlAdhiam Dam at 4m gate opening.

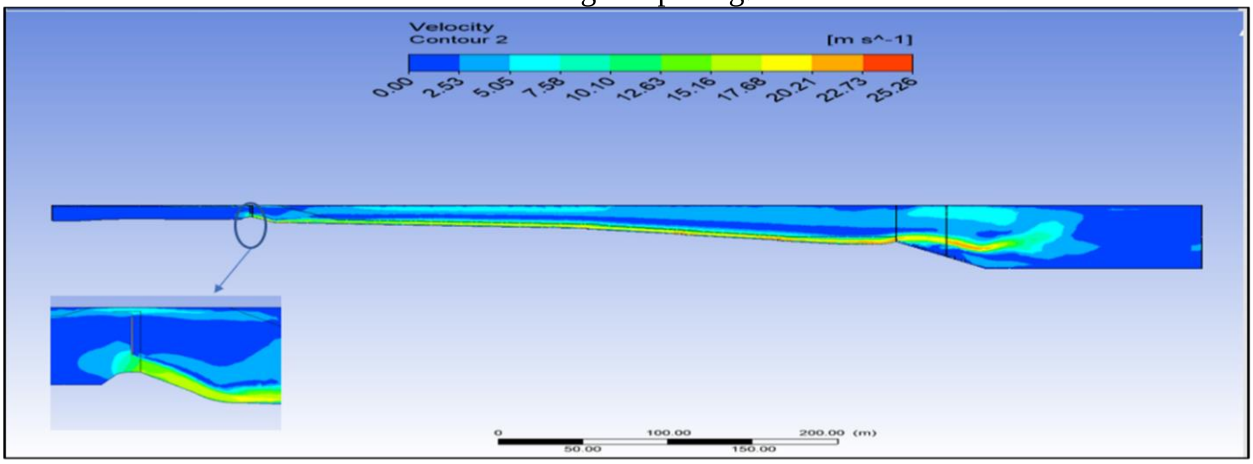


Figure 12. Velocity variation over the spillway and along the stilling basin of AlAdhiam Dam at 6m gate opening.

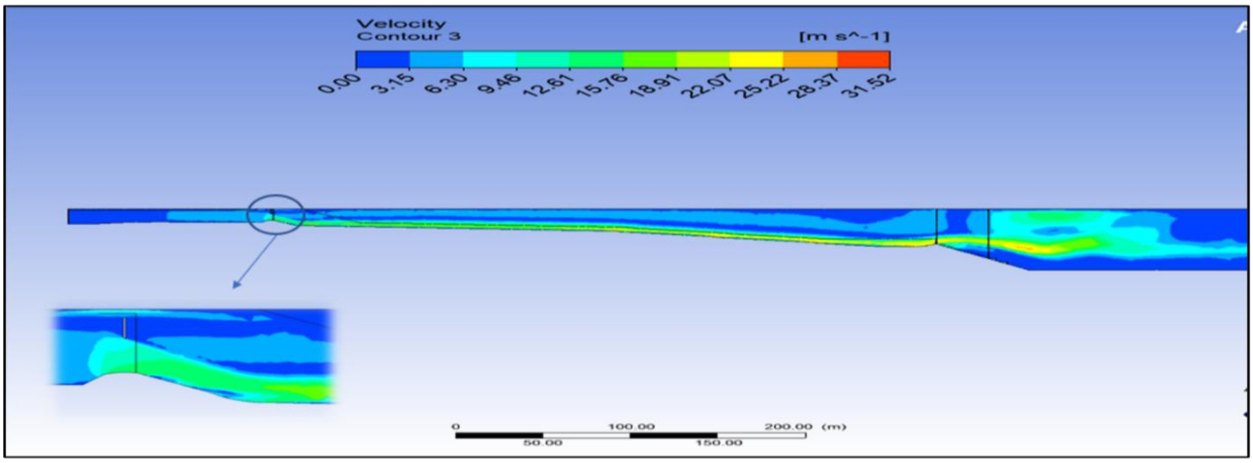


Figure 13. Velocity variation over the spillway and along the stilling basin of AlAdhiam Dam at 8m gate opening.

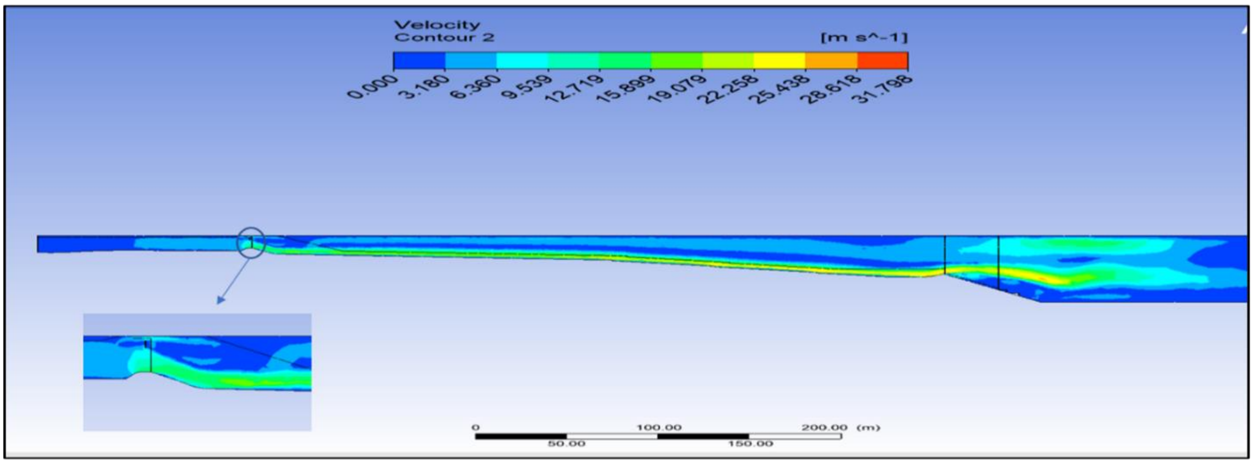


Figure 14. Velocity variation over the spillway and along the stilling basin of AlAdhiam Dam at 10m gate opening.

Fig. 15 to **Fig. 24** show the pressure variation over the spillway and along the stilling basin of AlAdhiam Dam under a different opening gate. A summary of the pressure variation is presented in **Table2.** The pressure variations along the spillway are dependent on the velocity variations and the water level in each section. The pressure at the inlet side of the spillway varied between (7.2 – 183) kPa depending on the gate opening. The pressure behind the gate is reduced to reach low negative pressure; a minimum value of the negative pressure is -54.05 to -58.59 kPa, which corresponds to gate openings of 2 and 10 m, respectively. After that, the pressure will be positive along the stilling basin except for some points on the drops in elevations and at the bucket. The pressure at the drops elevation at the 2m gate opening increased and varied from -25.45 to -28.28 kPa. At the 4 m gate opening, the drops elevation varied from -35.5 to -47.49 kPa, and at the 6m gate opening, the drops elevation also varied -50.8 to -57.32 kPa, at the 8 m gate opening the pressure at the drops elevation varies from -48.22 to -57.45 kPa and the pressure at the drops elevation at 10 m gate opening vary between -52.60 to -56.30 kPa. When the gate opens 10 m at the end of the flip bucket, the maximum value of the minimum negative pressure occurs, with a value of -459 kPa. At 2m gate opening, the lowest value of minimum negative pressure at the end of the flip bucket is -4.9 kPa.

Table 2. Different gate opening values and pressure variation

Gate open (m)	Pressure just behind the gate (kPa)	pressure in the drops elevation (kPa) drop1, drop2, drop 3	pressure at the end of the flip bucket (kPa)
2	-54.05	- 25.45, -21.93, -28.28	-4.9
4	- 56.04	-35.5, -42.49, -47.49	-174
6	- 57.2	- 50.8, -55.8, -57.32	- 193
8	- 58.25	- 48.22, - 45.62, - 57.45	- 376
10	- 58.59	-52.60, - 52.22, - 56.30	- 459

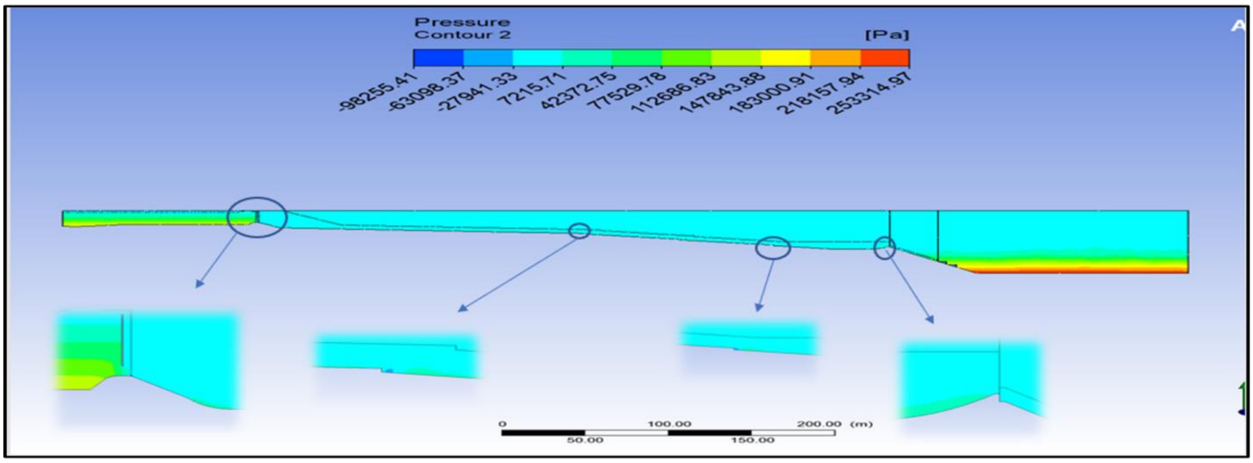
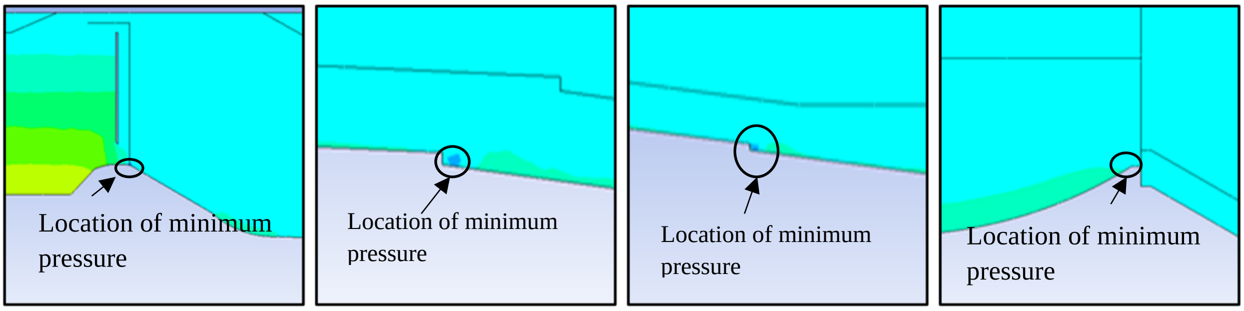


Figure 15. The pressure variation over the spillway and along the stilling basin of AlAdhiam Dam after opening gate 2m.



a- At the gate b- At drop elevation 1 c- At drop elevation 3 d- At flip bucket

Figure 16. Close up view of the negative pressure at a different locations after opening gate 2m.

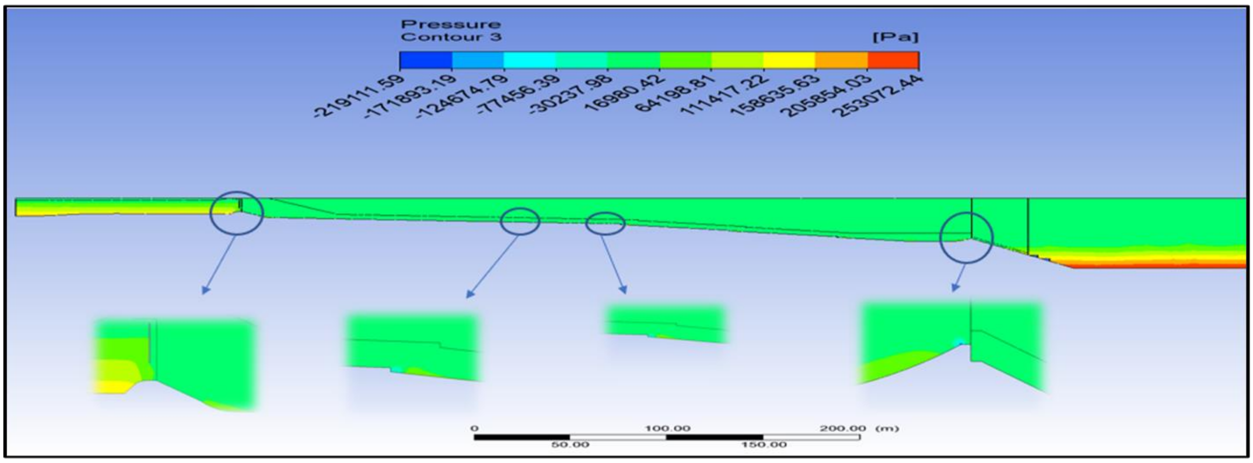
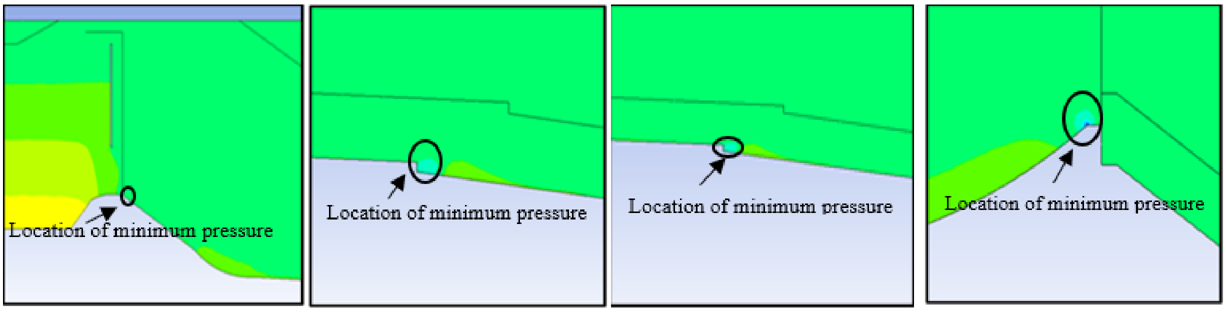


Figure 17. The pressure variation over the spillway and along the stilling basin of AlAdhiam Dam after opening gate 4m.



a- At the gate b- At drop elevation 1 c- At drop elevation 3 d- At flip bucket

Figure 18. Close up view of the negative pressure at a different locations after opening gate 4m.

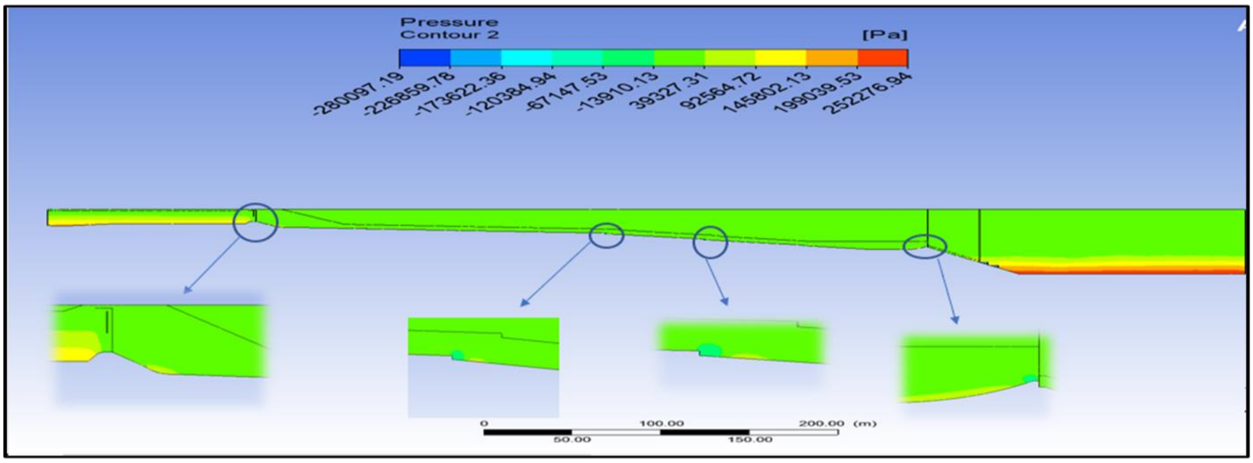
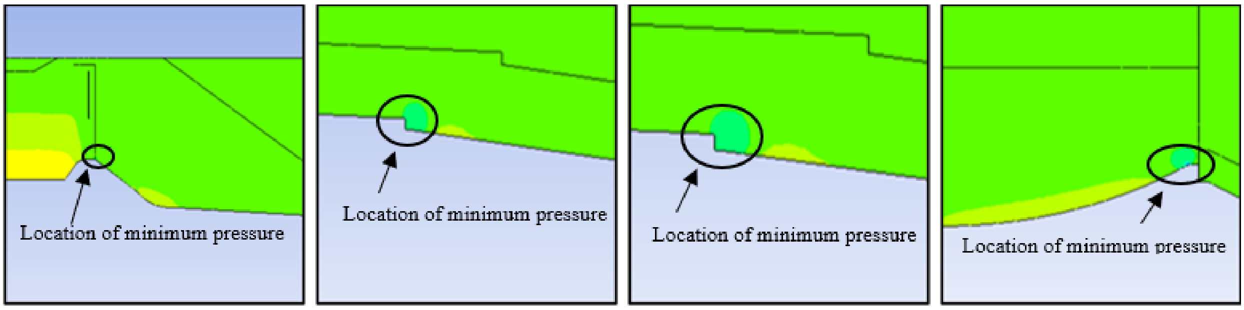


Figure 19. The pressure variation over the spillway and along the stilling basin of AlAdhiam Dam after opening gate 6m



a- At the gate b- At drop elevation 1 c- At drop elevation 3 d- At flip bucket

Figure 20. Close up view of the negative pressure at a different locations after opening gate 6m.

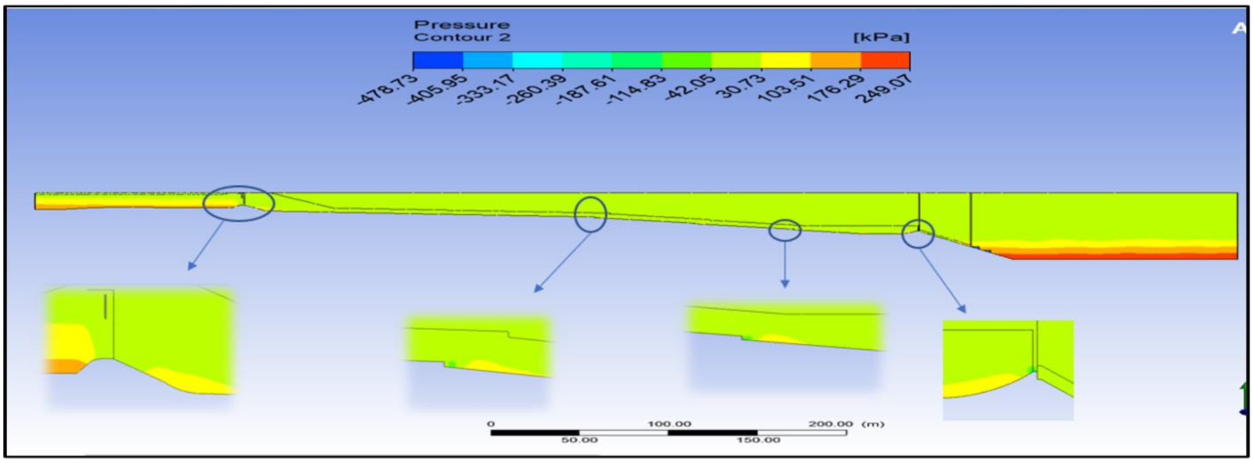
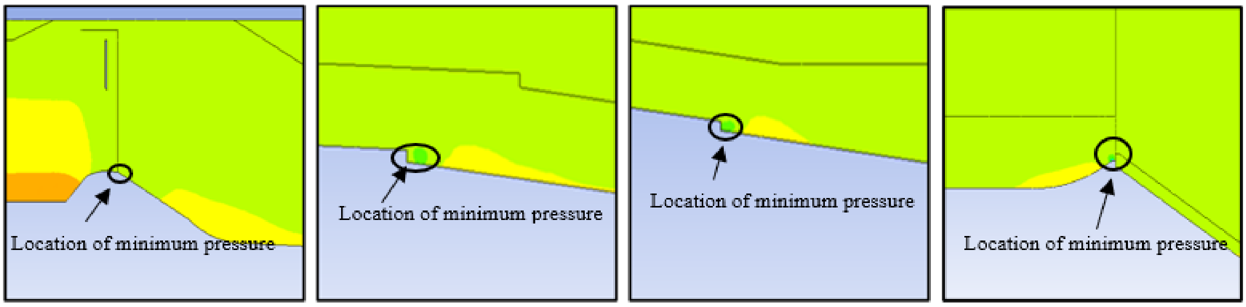


Figure 21. The pressure variation over the spillway and along the stilling basin of AlAdhiam Dam after opening gate 8m.



a- At the gate b- At drop elevation 1 c- At drop elevation 3 d- At flip bucket

Figure 22. Close-up view of the negative pressure at a different locations after opening gate 8m.

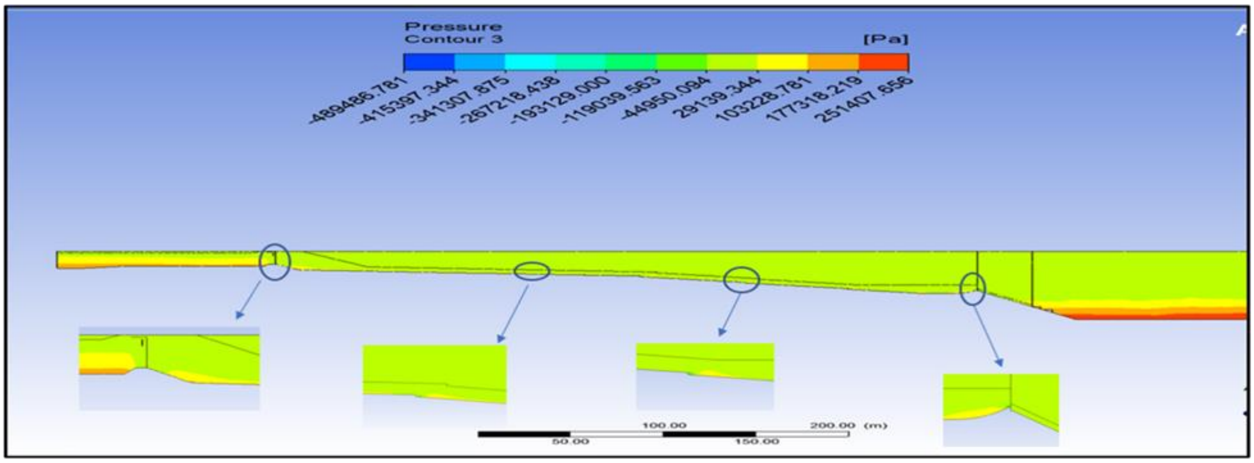
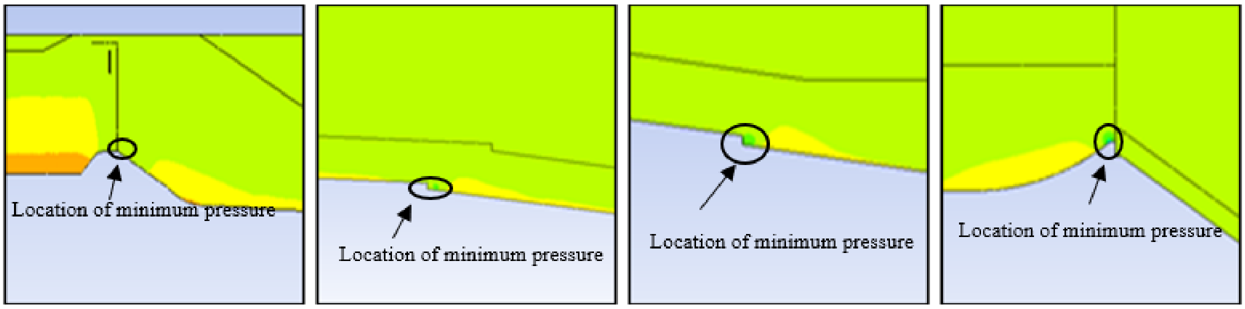


Figure 23. The pressure variation over the spillway and along the stilling basin of AlAdhiam Dam after opening gate 10m.



a- At the gate b- At drop elevation 1 c- At drop elevation 3 d- At flip bucket

Figure 24. Close-up view of the negative pressure at a different locations after opening gate 10m.

7. CONCLUSIONS

In this study, the flow over the Al Adhaim Dam ogee spillway was simulated in 3D using CFD techniques after being gated, and turbulence was modeled in the flow using an SST k-ω with the VOF approach. A tetrahedral mesh of 8 m was employed with the grid size. The result of this investigation of a spillway and the stilling basin of Al Adhaim Dam after gated conditions indicated the following conclusions:

1. The model accurately predicts the flow's design discharge and surface profiles along the spillway.

2. The spillway was capable of conveying the design flood wave over its crest.

3. The rating curve for gated conditions indicates that a maximum discharge of 1036.3 m^3/s corresponds to the gate opening 10*m*.

4. The flow velocity at the spillway's inlet side reached 1.6 *m/s*.

5. Negative pressures exist at a different points along the spillway; the maximum value of the minimum negative pressure occurs, with a value of -459 kPa at the gate opens 10 m. At 2m gate opening, the lowest value of minimum negative pressure -4.9 kPa.

6. Hydraulic jump occurs at different distances throughout the plunge pool depending on the incoming velocity in the flip bucket; the farthest distance from the spillway crest will be when the gate opens 10 *m*.

7. When placing the gate, the capacity increased by about 1.5 billion m^3.

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