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ESTIMATION AND SIMULATION OF PRESSURES ON THE PROFILE OF THE SPILLWAY

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Abstract*— Spillways are huge masonry structures constructed to discharge additional amount of water in needs and emergencies. It is also a measure to protect the structure from overtopping and failure. To achieve safety of the structure, the design of profile of the spillway plays a significant role. The forces that are generally possible on the spillway are as a consequence of change in pressures. This generates the necessity for estimation and understanding of pressures over the profile of the spillway. The present study was carried out to analytically estimate the pressures and compare them with the ANSYS-CFD simulation results. The analytical results estimated by the conventional equations were observed to have a fair agreement with the simulation results having a variation less than 2%.

***Keywords*— Spillway, Dynamic pressure, Maximum pressure, Fluent**

INTRODUCTION

Overflow spillways are designed to pass large volumes of water safely over the crest of the dam during floods. An overflow spillway is an open channel with large slopes with a rounded crest at its entry that permits the excess waters to flow over its surface profile at super critical velocities. Many researchers carried out physical modeling and simulation studies to evaluate the pressure parameters of the spillway. Contributing towards the estimation of Pressures, KhaniSalar et al (2017) conducted simulation analysis by a scaled model of flow over the flip bucket using CFD – Flow 3D software for Clyde dam spillway with a height of 64.5 m on Clutha River in New Zealand. The dam was designed to discharge 4100 cumec at PMF level of 195.1 m provided with a spillway length of 70 m leading to stilling basin provided with reverse slope of 1:8. The authors computed the theoretical values of pressures along the flip bucket curvature for different ratios of spillway design discharge ranging from 0.25 to 1.5Q_d. Their study declared that, the maximum pressure occurred at the midpoint of the horizontal length of the bucket curvature. They concluded that, the theoretical and simulated results had 23 to 41% deviation. Further, they added that numerical analysis was more reliable with the experimental studies wherein the theoretical pressure distribution was less erratic and subjected to vary, even with slight change in the slope [1].

Nazari et al (2013) analyzed the performance of chute flip buckets for various hydraulic and geometry conditions adopting experimental data of five different physical models. The aim of the study was to extort the understanding of minimum and maximum pressures and their exact concentration along the flip bucket. All the physical models were constructed based on the Froude’s similarity analysis. In the analysis, the dynamic pressures were measured by installing 0.1% accuracy pressure transducers with a pressure sampling rate of 100 Hz. From the model studies, the authors have developed a relation for maximum dynamic pressure and the location of minimum and maximum pressures based on the takeoff angle and chute slope. Further, the authors proposed two different equations for plotting the dynamic pressure distribution along the bucket and concluded that the upstream chute slope has a significant effect on the dynamic pressures [2].

Heller Valentin et al (2007) conducted physical studies on a prismatic chute at Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Switzerland with a circular-shaped flip bucket. The study mainly emphasized on framing of general design criteria for estimation of maximum dynamic pressure on the head of flip bucket, jet throw distance and flow chocking. The experiments were conducted for discharges upto0.186 m^3/s and were controlled by mean of an overflow weir. His study evaluated various parameter viz., maximum dynamic pressure, take-off angles for upper and lower jet trajectories and flow choking conditions using different equations. The author concluded the results by expressing various parameters as function of Froude’s number [3].

In the present study, yet an another step is taken to analytically estimate Dynamic pressure in the spillway bucket and maximum pressure at the invert level of the spillway bucket and compare them with the simulation results obtained from ANSYS-CFD.

CASE STUDY

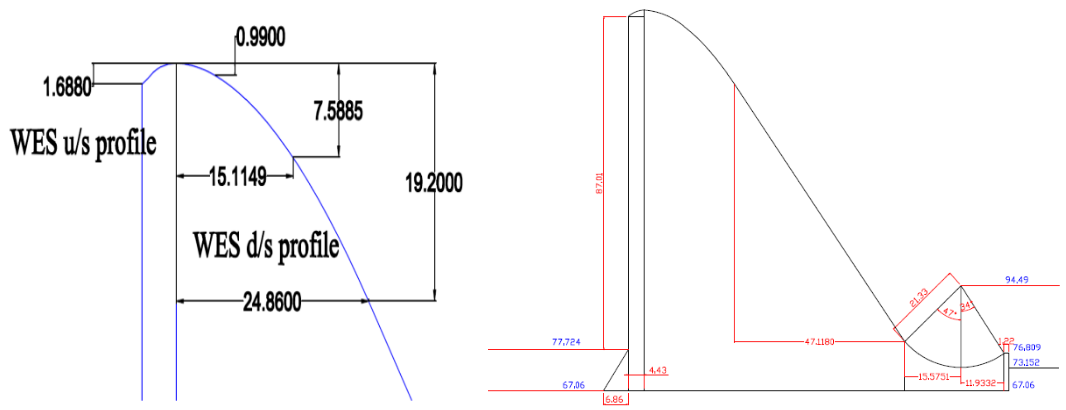
The study area of the present investigation consists of NagarjunaSagar project, built at 2.4 km downstream of Nandikonda village of MiryalagudaMandal of Nalgonda District in Telangana State. It is located at 79°18' 47" E longitude and 16°34'23" N latitude. The project comprises of 124.66 m (409 ft) high masonry dam with a total volume of water to be impounded 199 million cu ft. The salient features of the case study are highlighted in Table 1 [4].

TABLE 1
SALIENT FEATURE OF NS DAM

Description of Parameters	Details
Maximum Water Level (MWL)	181.100 m
Full Reservoir Level (FRL)	179.832m
Discharge (Q)	58,340 m^3/s
Top of the Dam (TOD)	184.40 m
Spillway Crest Level	166.421 m
Height of the spillway	166.421 – 67.06 = 99.361m
Maximum height of the dam	124.66 m
Length of spillway	470.916 m
Pier thickness	4.572m
Average River Bed Level	184.40 – 124.66 = 59.74 m
Size of each bay of crest gates	13.716 x 13.41m
Constants	K_p = 0.01 and K_a = 0.1

I. METHODOLOGY

The present study was carried out to focus and demonstrate the efficient application of numerical methods. The study involves estimation of diverse flow parameters on the spillway profile to simulate the flow behavior over the structure. Several standard Ogee shaped spillway profiles were developed by U.S. Army Corps of Engineers at Waterways Experiment Station (WES), such shapes are known as WES standard spillway shapes. In the present study, the spillway crest upstream profile was estimated by eq. (1) with origin at the crest of the spillway and downstream spillway profile was designed by the use of eq. (2) detailed below [5]. The curve extends $0.270H_d$ (X_c) on upstream and $0.125H_d$ (Y_c) below the crest point of the spillway as shown in the Fig. 1.



(a) (b)

Fig. 1 (a) WES Profile (b) WES profile Spillway

$$Y = \frac{0.724(X + 0.27H'_d)^{1.85}}{H_d'^{\,0.85}} + 0.126H'_d - 0.4315H_d'^{\,0.375}(X + 0.27H'_d)^{0.625} \text{.................. (1)}$$

$$X^n = K.H_d'^{\,n-1}.Y \text{ .... (2)}$$

where
X, Y = coordinates of the upstream and downstream profile (m)
n, K = variable parameters which depend on the inclination of the upstream face of the dam, n = 1.85 and K = 2.0
H'_d = Design head (m)

The dynamic pressure on the profile of the spillway, in the bucket invert and at the exit level is exerted by the force of flowing water. There is a continuous change in the velocity in the spillway bucket section. Therefore, the dynamic pressures at the above sections were estimated by the application of Impulse Momentum equation, by neglecting the friction on the spillway and approach velocity. Gumenesky and Balloffet gave the following eq. (3) and eq. (4) for estimating the pressure head on the curved surface of the spillway by considering even the centrifugal effects. The total head at the end of the section is taken as the summation of pressure terms due to centrifugal effects and the weight of the fluid in the section. The first term in their equations is the pressure head due to static conditions, and the second term represents the pressure head due to centrifugal effects.

Gumenesky's equation $$h_d = \left(1+\frac{V_a^{\,2}}{gR}\right).h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Balloffet's equation $$h_d = h + \frac{V_a^{\,2}}{2g}\left[1+\left(\frac{R-h}{R}\right)^2\right] \quad \ldots\ldots\ldots\ldots (4)$$

In the above equations,

$$\frac{V_a}{V_T} = k \quad \ldots\ldots\ldots\ldots\ldots (5)$$

The value of 'k' can be obtained from the chart shown in the Fig. 2 [7].

$$V_T = \sqrt{2g(H-0.5H_d)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where
H_d = head over the crest (m)
V_T = velocity at the toe of the spillway (m/s)
h = water depth at the bucket invert (m)
h_d = design pressure head at the bucket invert (m of water)
V_a = actual velocity (m/s) and k = constant

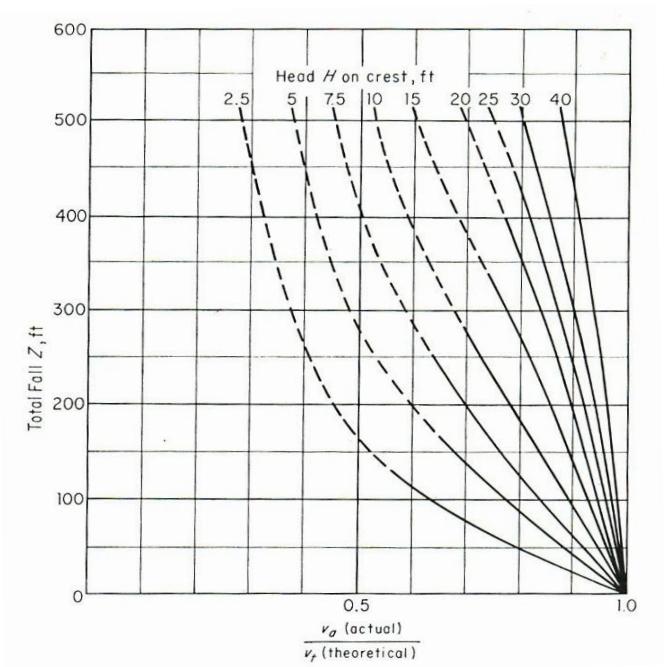


Fig. 2 Relation of Actual and Theoretical Velocities [7]

The maximum pressures at the invert level of the bucket were estimated from eq. (3). The value of H (93.268 m) was computed by subtracting bucket invert level (73.152 m) from the crest level of the spillway (166.42 m). Further, the head over the crest (H_d) was taken as 13.412 m, i.e., the difference between FRL (179.832 m) and crest level of the spillway (166.42m). The total pressure heads in the bucket were estimated by adopting eq. (5) and eq. (6). The computed values are detailed in Table 2.

TABLE 2
DYNAMIC AND MAXIMUM PRESSURE ALONG FLIP BUCKET

Discharge	Dynamic Pressure in the Bucket ($P_{dyn(c)}$)	Maximum Pressure at the invert of the bucket ($P_{max(c)}$)	
		Gumenesky's Formula	Balloffet's equation
cumec	Pa	Pa	Pa
58340	2882417.206	220040.8551	207616.775
43,755	2854942.333	164325.4849	157396.535
29,170	2837707.942	109187.0609	106127.917
14,585	2811427.95	54417.24133	53657.3865

SIMUALTION ANALYSIS

The model studies are performed even today for understanding various flow parameters in hydraulic structures. These are considerably expensive requiring lot of man-power, electric power, water, and material leading to time-consuming process to build and also to alter. The present study was taken up to investigate the possibilities of using a numerical simulation method in order to facilitate the ease in the design process of a spillway. The advantage of this method is to save time and resources by altering the spillway parameters in the numerical model. The proposed design to be adopted for implementation can also be verified using physical modeling, if required. The model of spillway was taken as an obstruction in between the rectangular domain. The simulations were performed on the 1:100 scale model of the spillway section of NagarjunaSagar Dam by considering Froude's model law. The geometry and meshing were created in GAMBIT software as shown in Fig. 3 and Fig. 4 respectively. Fine mesh was adopted for better accuracy of the results. The mesh was made of 0.01 cell size and 95,000 numbers of nodes of paved sections, made up of Quadra-triangular cells.

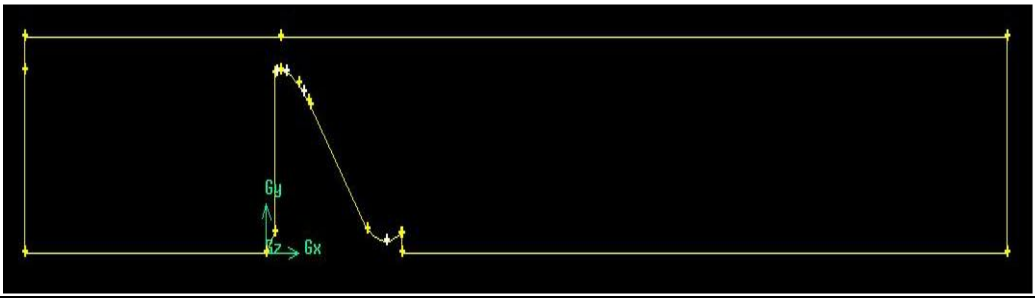


Fig. 3 Geometry of WES profile Nagarjunasagar Dam

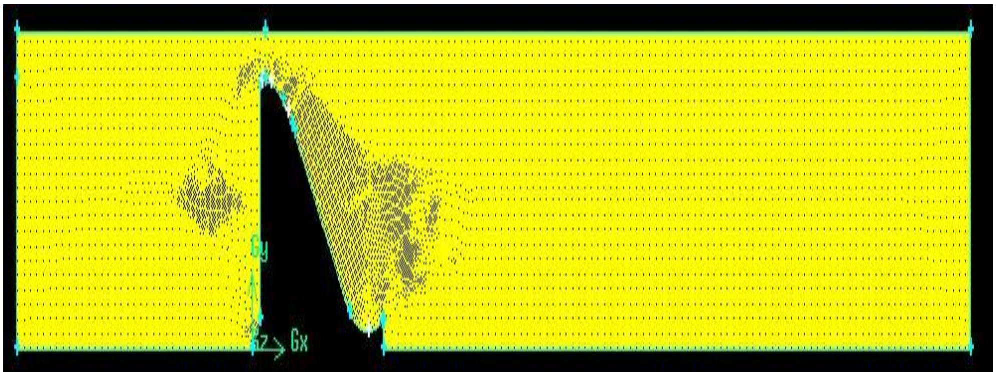


Fig. 4 Mesh of WES Profile Nagarjunasagar Dam

The boundary conditions adopted were velocity inlet over the crest level of the spillway to define the velocity flowing over the crest of the spillway; pressure outlet on the downstream end of the domain and on top of the domain for both the sides of the spillway. Further, the rest of the boundaries of the geometry were assigned as wall with no-slip condition. The Fluent solver was adopted to determine the spillway parameters for four different discharges viz., maximum discharge of Q = 58340 cumec, 0.75Q, 0.5Q and 0.25Q. Each velocity was assigned for solving various equations such as Continuity, X - Velocity, Y - Velocity, k and ε – equation, leading to convergence. For each time step 20 iterations were taken to attain convergence. The computational time ranged from 4 to 6 hr for attaining the convergence criteria and the flow to fall into the bucket and hit the downstream side of the spillway. The required solution was observed to converge for 900 time steps and at 6500 iterations. For the two dimensional steady state in compressible flow, the Reynolds-Averaged Navier-Stokes equations are given below [8].

$$\frac{\partial \bar{u}}{\partial x}+\frac{\partial \bar{v}}{\partial y}=0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$\rho\left(\bar{u}\frac{\partial \bar{u}}{\partial x}+\bar{v}\frac{\partial \bar{u}}{\partial y}\right)=-\frac{\partial \bar{p}}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial \bar{u}}{\partial x}-\rho u'u'\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial \bar{u}}{\partial y}-\rho u'v'\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

$$\rho\left(\bar{u}\frac{\partial \bar{v}}{\partial x}+\bar{v}\frac{\partial \bar{v}}{\partial y}\right)=-\frac{\partial \bar{p}}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial \bar{v}}{\partial x}-\rho u'v'\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial \bar{v}}{\partial y}-\rho v'v'\right)\ldots\ldots\ldots\ldots (9)$$

In the eq. (8) & (9), the terms $-\rho u'u'$, $-\rho v'v'$ and $-\rho u'v'$ behave like stress terms, the first two terms are normal stresses and the last term is a shear stress. The present investigations were carried out using k – ε model

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=\tau_{ij}\frac{\partial U_i}{\partial x_j}-\varepsilon+\frac{\partial}{\partial x_j}\left[\left(\nu+\nu_T/\sigma_k\right)\frac{\partial k}{\partial x_j}\right]\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

The first term on the LHS of eqn. (10) represents the rate of change of k or ε and the second term explains the transport of k or ε by convection. While the first term on the RHS symbolizes the rate of production of k or ε, the second term demonstrates the rate of destruction of k or ε and the third term illustrates the transport of k or ε by diffusion.

Dissipation Rate:

$$\frac{\partial \varepsilon}{\partial t}+U_j\frac{\partial \varepsilon}{\partial x_j}=C_{e1}\frac{\varepsilon}{k}\tau_{il}\frac{\partial U_i}{\partial x_j}-C_{e2}\frac{\varepsilon^2}{k}+\frac{\partial}{\partial x_j}\left[\left(\nu+\nu_T/\sigma_\varepsilon\right)\frac{\partial k}{\partial x_j}\right]\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The production and the dissipation terms of eq. (11) are formed from the production and dissipation terms of the turbulent kinetic energy scaled by ε/k and multiplied by empirically determined constants and wall damping functions (C_{e1} and C_{e2}). An additional damping function must be included for the eddy viscosity in the k-ε equation by near walls so that k and ε will have the proper behavior in the near region. The Closure coefficients and auxiliary relations are given below:

C_{e1} = 1.44, C_{e2} = 1.92, σ_k = 1.0, σ_ε = 1.3, $\omega = \varepsilon/(C_\mu k)$.

In order to numerically trace the rapidly varying flow path over the spillway, it is very essential to track the free surface flow perfectly. This process involves three stages viz., identifying the surface, initializing this surface as an interface between air and water, and finally assigning the boundary conditions to the interface. In the present analysis, widely adopted and user friendly k-ε turbulence model was used to simulate the flow by Volume of Fluid (VOF) approach. The volume fraction of water was computed for the cells packed between the upstream and downstream of the spillway. The liquid level in the reservoir is allowed to maintain at FRL (Full Reservoir level) even for the maximum probable flood (MPF) by opening the additional gates as and when required. The fluid level inside the reservoir may reach above the FRL upto Maximum Water Level (MWL) for a limited duration without endangering the safety of the project. Further, for better and faster convergence, the flow level was patched upto FRL, 13.41 m above the crest level of the spillway as shown in Fig. 5.

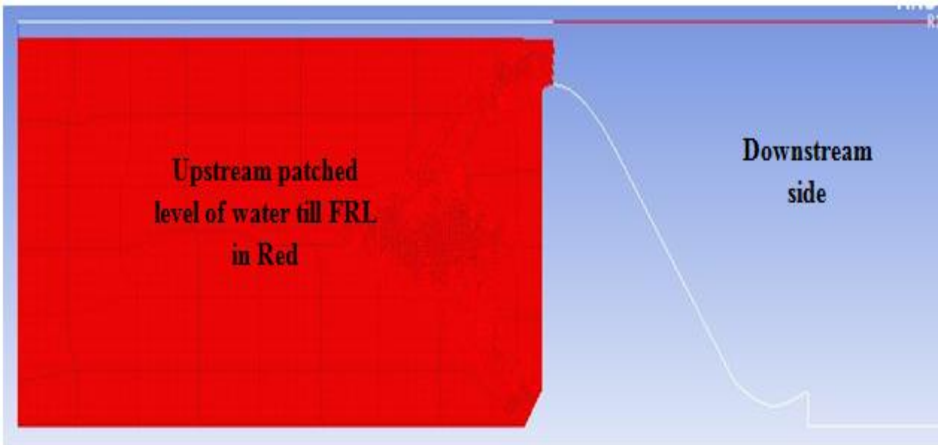


Fig. 5 Patched Water Level

The unexpected dissimilarity in the flow geometry associated with high flow velocity will result in turbulence and rigorous pressure instability. Further, this instability causes severe damage to the sloping profile and the bucket of the spillway. The contours of dynamic pressure in the bucket obtained from the simulation analysis are shown in Fig. 6.

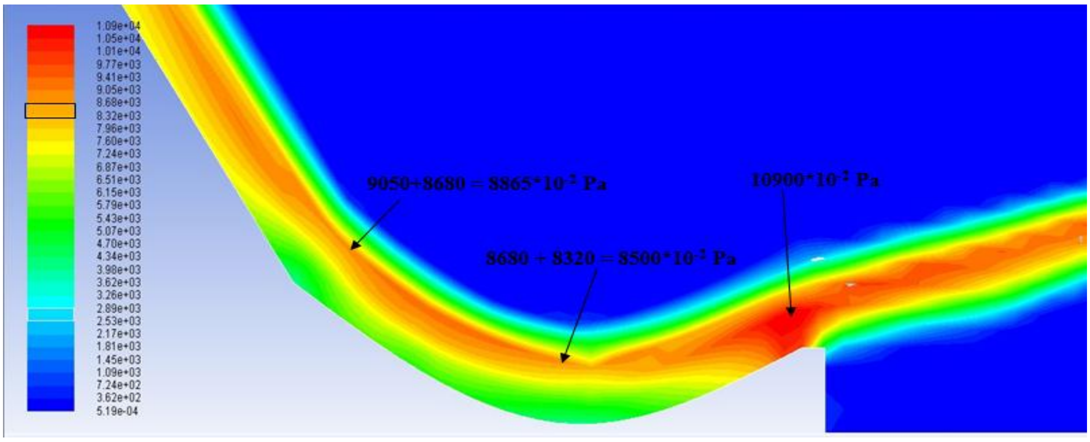


Fig. 6 Dynamic Pressures in Bucket (V = 8.309m/s)

The simulated values of dynamic and maximum pressures are highlighted in Table 3. The contours of dynamic pressure over the spillway profile as obtained from the simulation analysis are presented in Fig. 8. The pressure developed on the crest of the spillway as can be seen from Fig. 7, will be small and will not induce cavitation. The simulated values of flow velocities as well as dynamic pressure in the bucket are listed in the Table 3. These values are in good agreement with computed values as presented in Table 2.

TABLE 3
SIMULATED RESULTS OF DYNAMIC PRESSURE AND MAXIMUM PRESSURE (V = 8.309 M/S)

Description	Notation	Simulated Values
Dynamic Pressure in the Bucket (Pa)	$P_{dyn(s).}$	2826500
Maximum Pressure at the Invert of the Bucket (Pa)	$P_{max(s)}$	217700

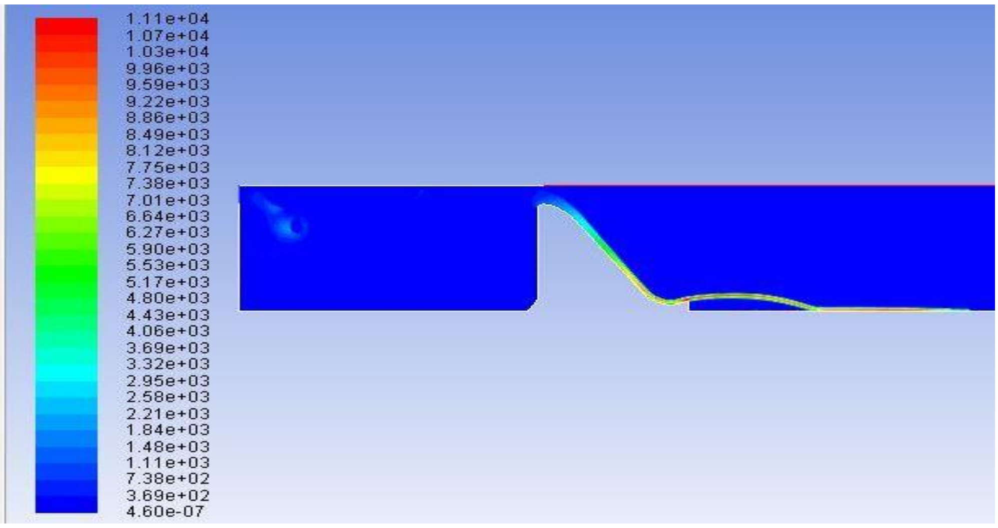


Fig. 7 Dynamic Pressures over the Spillway

II. RESULTS AND DISCUSSION

Based on the present analytical computations and simulation results over the spillway, the following results were deduced

- The present study was carried out on WES profile Nagarjunasagar spillway for four different discharges.
- The numerical simulations were carried out on a scale down model of 1:100 with k-ε turbulence model. The results were interpreted from a User Defined Function and execution of volume fraction macro.
- The percentage error between analytical estimates and simulated values for the dynamic pressure in the bucket is less than 2%. Therefore, the simulated results of dynamic pressures were found to be acceptable harmony with the analytical values as highlighted in the Table 4. As per KhaniSalar (2017) study the maximum pressure occurred at the midpoint of the horizontal length of the bucket curvature. They concluded that the theoretical and simulated results had 23 to 41% deviation.

TABLE 4
COMPARISON OF DYNAMIC PRESSURE

Computed Dynamic Pressure in the Bucket (P_{dynI})	Simulated Dynamic Pressure in the Bucket ($P_{dyn(s)}$)	Error
Pa ($x10^6$)	Pa ($x10^6$)	%
2.8824	2.8265	1.94
2.8549	2.8045	1.77
2.8377	2.7955	1.49
2.8114	2.7735	1.35

- The computed and simulated results of maximum pressure at the invert level of the bucket showed an increasing variation with the error percentage ranging from 1.06 to 1.23% leading to the significant effect of air entrainment as highlighted in Fig. 8. From Fig. 8, it is manifest that Gumenesky's formula gives a better estimate over Balloffet's equation.

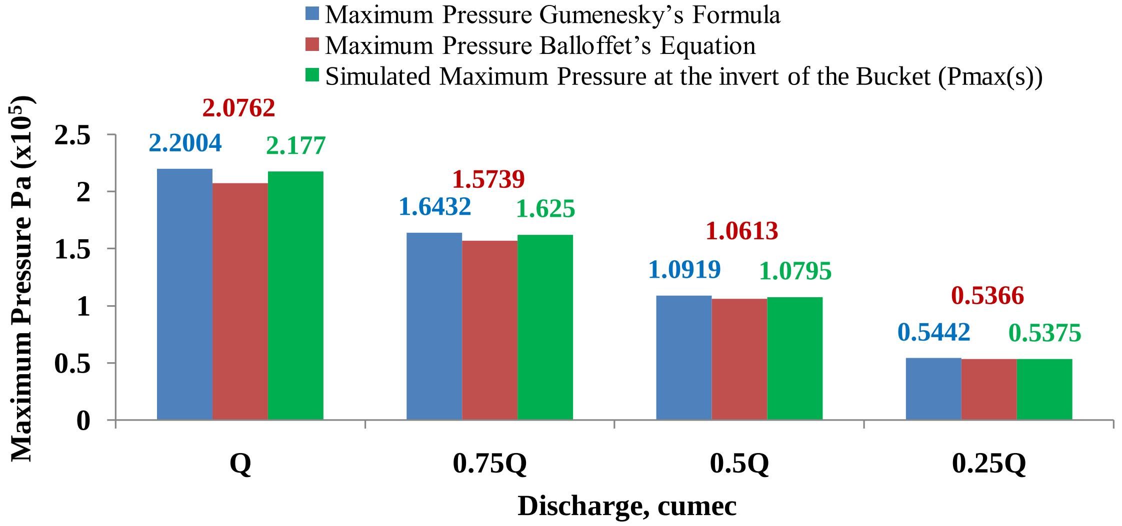


Fig. 8 Comparative analysis of maximum pressure

CONCLUSIONS

From the literature, it was observed that limited studies were available regarding the analytical estimation of dynamic and maximum pressures using traditional equations. In the present investigations, the simulated results of dynamic pressures were found to be in acceptable harmony with the analytical values. The error percentage was observed to be less than 2% for Dynamic pressure values. The computed and simulated results of maximum pressure at the invert level of the bucket showed an increasing variation with the error percentage ranging from 1.06 to 1.23%.

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