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Performance of Hydrodynamics Flow on Flip Buckets Spillway for Flood Control in Large Dam Reservoirs

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Abstract

Flip buckets are usually used in high head dams to dissipate the destructive energy of high-speed jets. These structures are fixed at the ends of the outlet conduits to direct the moving jet into the atmosphere. The process of energy dissipation also resumes while the jet enters its downstream plunge pool. Although studies of flow over flip buckets date back to many years ago, there are still uncertainties regarding the flow behavior over these structures with various geometries and flow conditions. In this study, experimental measurements of static and dynamic pressures and their distribution over these structures are investigated. Measurements were made along two different simple flip buckets with various Froude numbers to determine the effects of the geometry and flow characteristics on the pressure field. Maximum pressures are also presented, and the results are compared with those of other investigations. The results of this study can be used to increase the safety of large dams that remain sustainable in the process of exploitation, such as irrigation, human consumption, industrial use, aquaculture, and navigability.

Keywords: River; Pressure Distribution; Dynamic Pressure; Chute Spillway; Flow.

1. Introduction

A large dam is a barrier that prevents or limits the flow of surface water or underground streams. Reservoirs created by dams not only suppress floods but also provide water for activities such as irrigation, human consumption, industrial use, aquaculture, and navigability [1-3]. A large dam can also be used to collect or store water, which can be evenly distributed between locations. Large dams generally serve the primary purpose of retaining water, while other structures such as floodgates or dikes (also known as levees) and spillways are used to manage or prevent water flow into specific land regions. A spillway is a structure used to provide the controlled release of water from a dam or levee downstream, typically into the riverbed of the dammed river itself [4]. In some references, they may also be known as overflow channels. Spillways ensure that water does not damage parts of the structure not designed to convey water. A chute spillway is a simple design that transports excess water from behind a large dam down a smooth decline into a river downstream. These are usually designed with an ogee curve spillway. They are typically lined with concrete on the bottom and sides to protect the dam and topography. They may have a controlling device, and some are thinner and multiply-lined if space and funding are tight. In addition, they are not always intended to dissipate energy like

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stepped spillways, flip buckets, or ski jumps [5-7]. Chute spillways can be ingrained with a baffle of concrete blocks but usually have a "*Flip Lip*" and/or dissipator basin, which creates a hydraulic jump, protecting the toe of the dam from scour.

Flip buckets are usually placed at the end of chute spillways and outlets of high dams to project the high velocity flows issuing from these structures. The outlet jet moves through the atmosphere and then enters into a plunge pool, which both help to dissipate the destructive energy of the jet. Until 1950, the flip bucket design was often performed without considering centrifugal forces caused by flow rotation within the bucket. Generally speaking, the total dynamic pressure on the bucket is the sum of hydrostatic and centrifugal effects in the form of Equation 1 [8]:

$$P = h_0 + \frac{h_0 V_0^2}{gR} \tag{1}$$

Balloffet (1961) [9] simulated the velocity distribution within flip bucket by irrotational flow hypothesis ($V.R$=Constant) and then presented its pressure distribution as Equation 2;

$$P_{\max} = h_0 + V_0^2 / 2g(1-((R-h_0)/R)^2) \tag{2}$$

In the above equations, P_{max} is the maximum pressure, h_o and V_o are respectively the depth and velocity of entering flow to the bucket, R is the radius of the bucket and g is the acceleration of gravity. In (1963), Tierney and Henderson showed that for low values of h_o/R, the experimental results are in reasonable agreement with those obtained from vortex potential theory with deflection angles less than 45° [10]. In (1965), Chen and Yu determined the pressure distribution along circular buckets using potential theory for deflection angles between 75° to 95° [11]. Their results for maximum pressure were close to those of Balloffet. In (1969), Lenau and Cassidy modified Chen and Yu theory and gained a set of equations by assuming an incompressible and irrotational flow. They solved these equations to determine the pressure and velocity distribution within the bucket and showed that the effect of viscosity is insignificant, but the effect of centrifugal force is important. If the pressure (P) made dimensionless by Head of water (H) in the form of P/ρgH, also [11];

$$P/(\rho V^2/2) = (1/2)[P/(\rho g h_0)].[F_0^{-2}] \tag{3}$$

where, $F_0 = V/(gh_0)^{0.5}$ is the entering Froude number of flow to the bucket, h_0 is the water depth and R is the radius of bucket. Thus, the maximum pressure within the bucket is a function of its curvature, relative depth of water (h_o/R) and the entering Froude number of flow.

Steiner et al. (2008) [12] conducted series of experiments to determine maximum pressure head and pressure distribution along the triangular-shaped buckets. The Pressure was measured along the approach flow channel and the deflector using conventional pressure taps. The pressure head line was plotted to define the location x_{PM} of the maximum pressure head. The dynamic pressure head distribution $h_{P(x)}$ along the deflector was analysed using the maximum pressure head characteristics (x_{PM}; h_{PM}). Depending on the empirical parameter Γ=(h_0/w)(sinγ/F), two types of pressure distributions were presented. For $\Gamma \le 0.057$, ie., for relatively large F_0 and w, and a small γ the dynamic pressure head distribution is sharp peaked, whereas it is fuller if $\Gamma > 0.057$.

A review of the technical literature concludes that, various models with different geometries of simple, complex, and inclined flip buckets have been studied. However, still systematic information should be collected to improve our knowledge on flow over these structures. Therefore, in this work, scaled models of left and right flip buckets of Gotwand dam in southern province of Iran were constructed and examined. The buckets are positioned at different altitudes. They are in circular shapes and longitudinally straight (with no inclination). Their upstream chute spillways are rectangular with similar slope of 3.5%. It was tried to determine a relationship between these parameters, based on experimental data from model studies of Gotwand dam. The results are then compared with those of previous investigation.

2. Materials and Methods

Upper Gotvand Dam, or simply the Gotvand Dam, is an embankment dam on the Karun River about 12 km (7.5 mi) northeast of Gotvand in Khuzestan Province, Iran. The main objectives of Gotvand Dam are to supply downstream irrigation water, control river inundations and generate hydropower energy. Location, overview of Gotvand Dam and details of chute spillway are shown in Figure 1.

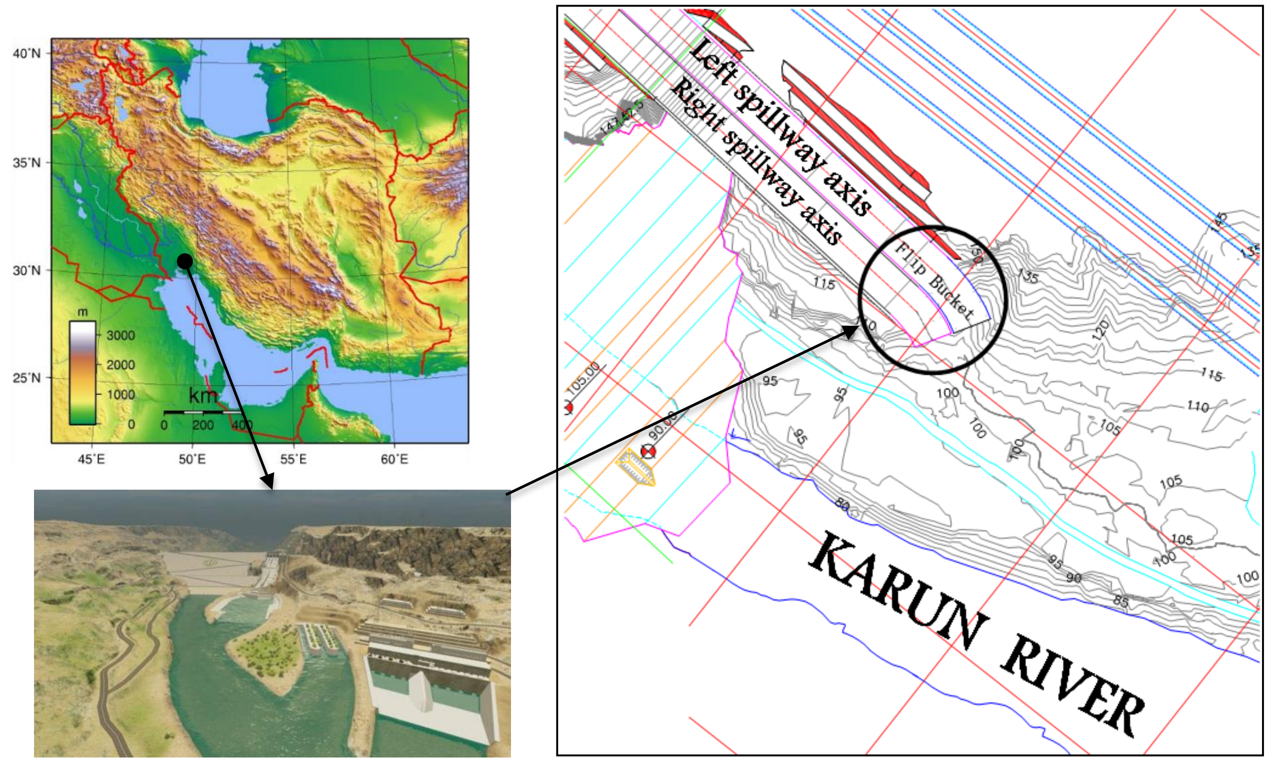

Figure 1. The location of the Upper-Gotvand Dam, Reservoir, and the Karun River (Iran)

Generally in the hydraulic structures e.g. spillways in which, free surface flow exists, the appropriate governing forces are the gravity and inertial forces. Thus, in order to construct the physical model and determine the scale under such conditions, similarity law was applied. The similarity condition has been chosen such that the flow regime in the model and prototype is identical. Because of the surface tension effects, the lower limit of 3 cm is commonly suitable for the depths [13]. However, this value has been proposed by some other references to be at least 1.5 to 2 cm [14].

According to the model conditions and limitations, a scale model (length scale 1/100) was used. In Gotwand model, flip buckets are placed at the end of two chute spillways, each has 34.5 cm width and 2 m length. They are made of Plexiglass to visualize the flow pattern. The altitudes of the two buckets are different, but the radius of the buckets is R=50cm and their deflection angle is β=28°. According to the flow condition and formation of the scour holes at the downstream of the flip bucket, two similar buckets were used. The only diffrence between the jets is their bed elevation which changes the impact lcation of them. This leads to a lower depht of the scour hole formed at the downstream of the flip buckets. Figure 2(a) presents the hydraulic model of Gotwand dam and Figure 2(b) demonstrates the geometry characteristics of the left bucket.

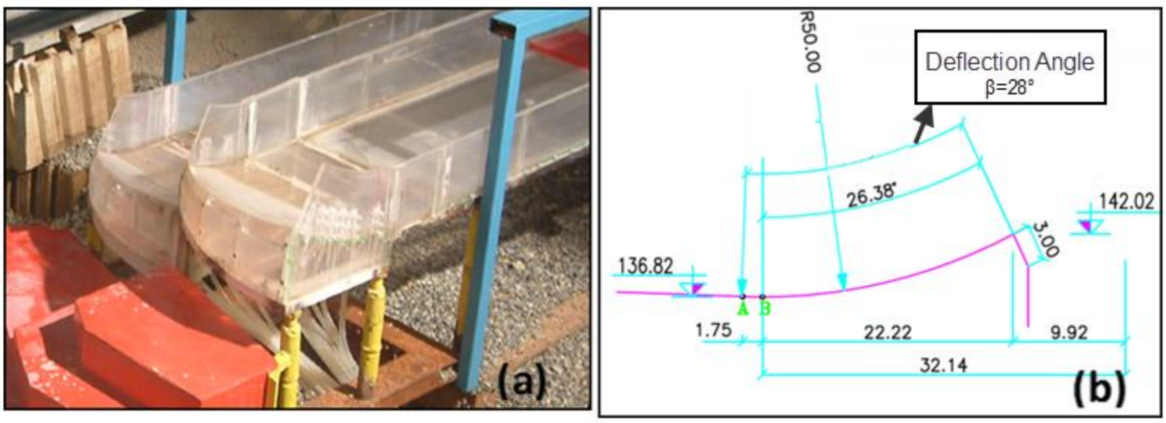

Figure 2. (a) Gotwand hydraulic model of the flip Buckets; (b) Geometry characteristics of the left bucket (all dimensions in centimeters)

Measurements of pressure on the bucket were made with different discharges (from 20-120 lit/sec). The presssure is measured by the digital paressure gauges. As a result, the mean velocity and depth of entering flow (ho) varied and thus, the entering Froude number changes from Fr=3.5 to 7.5. A set of pressure tubings were fixed at different cross sections of the buckets to measure the pressure. It includes the centerline and close to the walls. Figure 3 shows the position of these pizeometers on the two buckets [15].

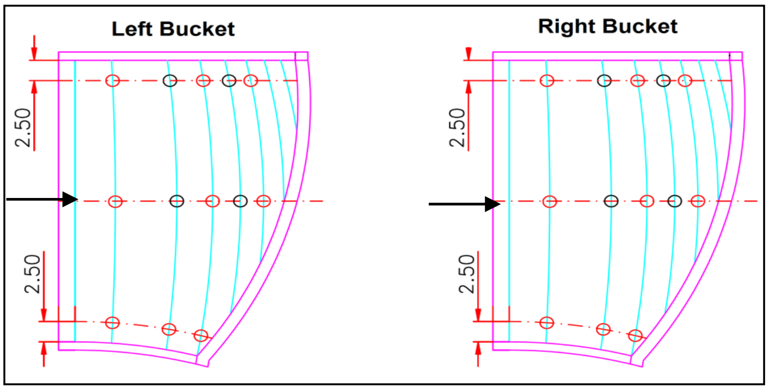

Figure 3. Position of pizeometers on the left and right scaled models of the buckets (plan view)

3. Results and Analysis

After the measurements, determination of static and dynamic pressure distribution on the bucket is an important task, which is used to design and check the stability of such structures. Figure 4 shows the free jets performed on the bucket [16].

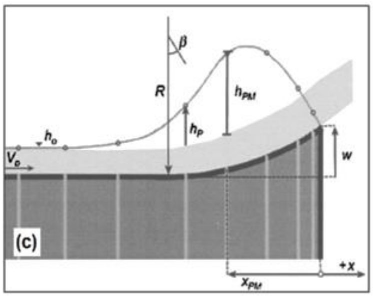

Figure 4. Static and dynamic pressure caused by free jet on the bucket

Figure 4 presents the dynamic pressure distribution and the position of its maximum on the bucket. Figures 5 to 10 show the experimental results of the static and dynamic pressure on the chute and on the bed of the left and right buckets, respectively. As the static pressure is a function of flow depth, it is possible to measure and calculate both static and dynamic pressures on the bed and the side walls. However, attention has been given to present the dynamic pressures. In Figure 4 rapid variation of Pressure distribution on the buckets is distinguished.

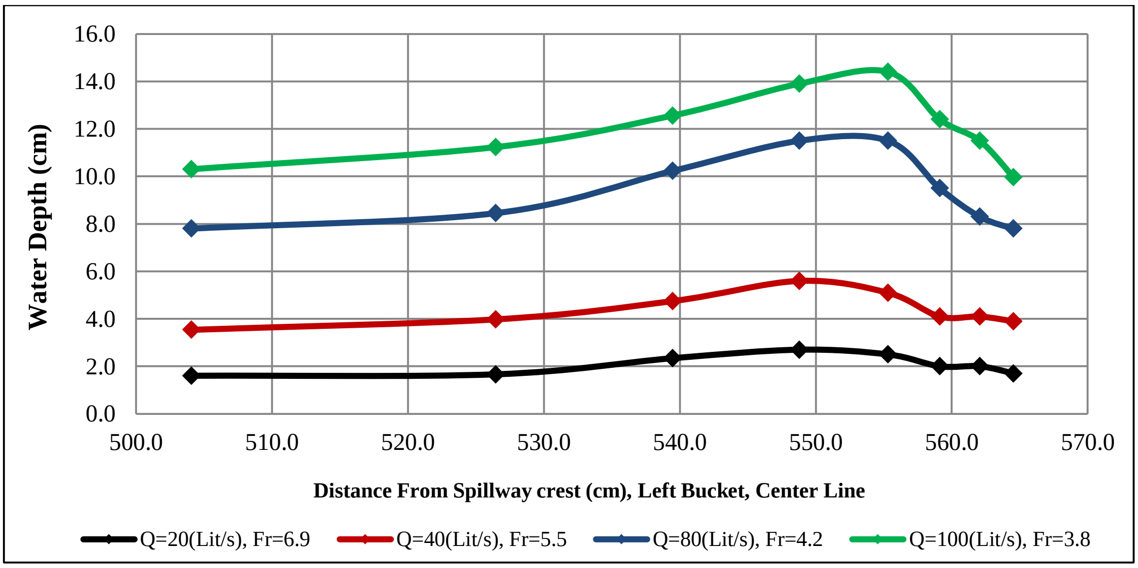

Figure 5. Variation of dynamic pressure on the left bucket along the Centreline

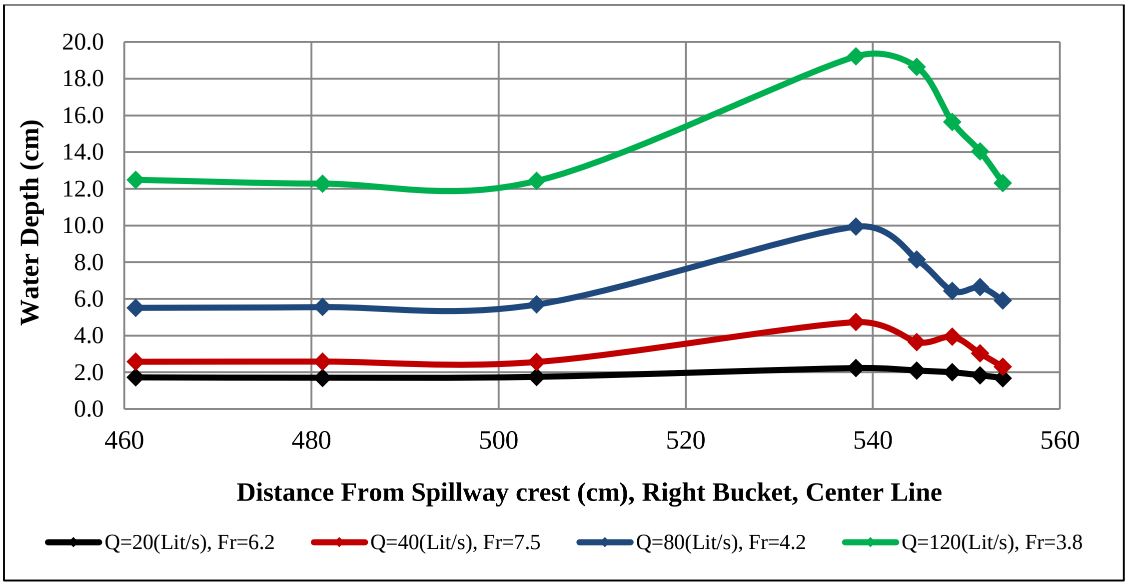

Figure 6. Variation of dynamic pressure on the right bucket along the Centreline

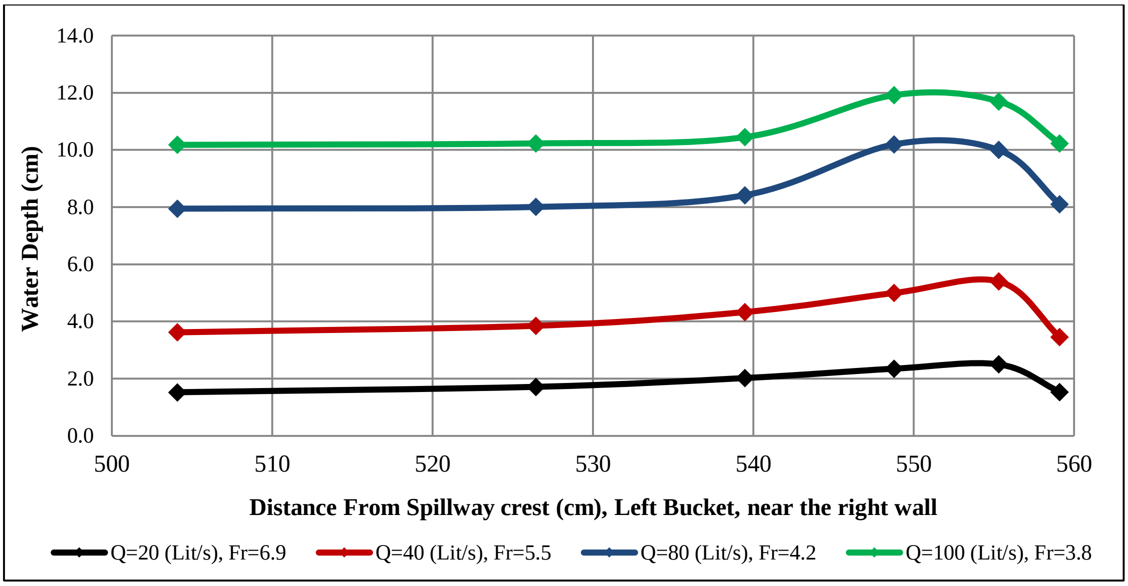

Figure 7. Variation of dynamic pressure on the left bucket near the right wall

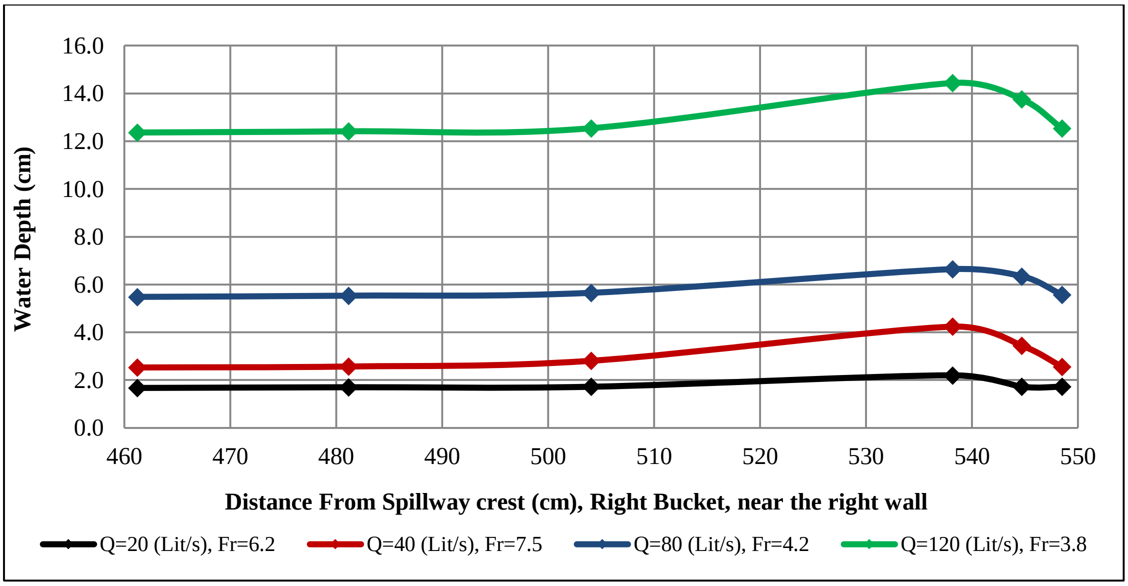

Figure 8. Variation of dynamic pressure on the right bucket near the right wall

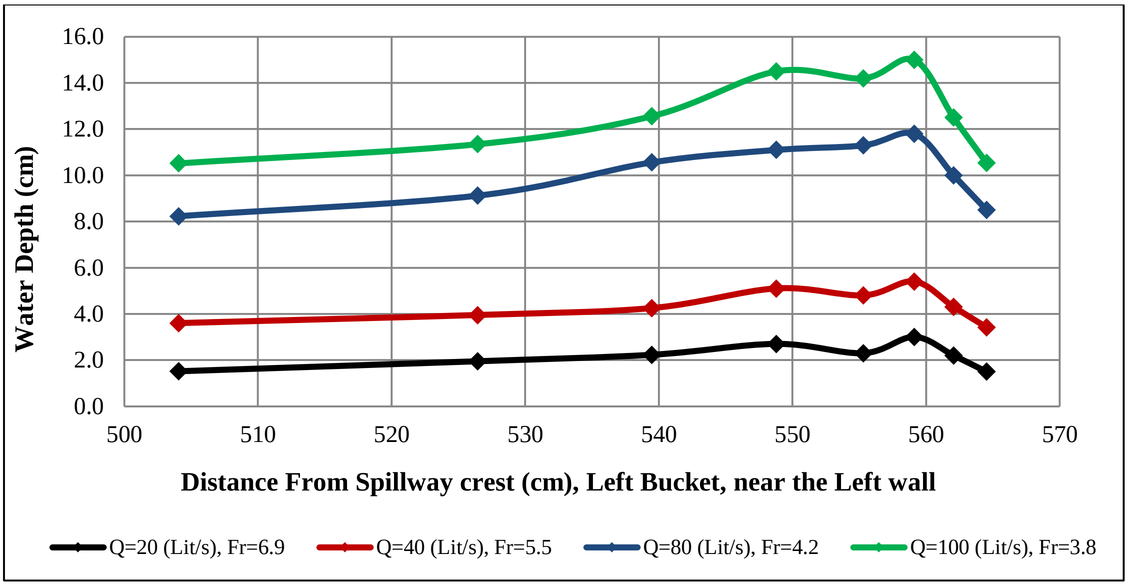

Figure 9. Variation of dynamic pressure on the left bucket near the left wall

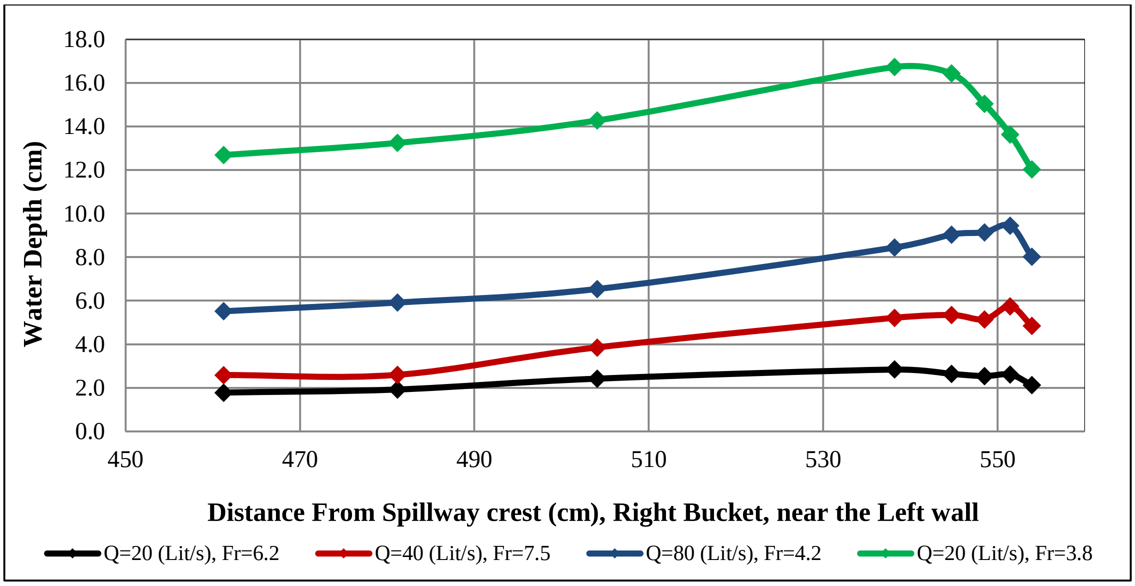

Figure 10. Variation of dynamic pressure on the right bucket near the left wall

To present the results, a dimensionless parameter, H_p, was introduced in the following form, which its distribution on the bucket can be presented based on the bucket geometry and its hydraulic characteristics [17];

$$H_P = (h_P - h_0) / (h_{PM} - h_0) \tag{4}$$

Where, h_p, ho and h_{PM} are respectively the longitudinal total, static and maximum pressures on the bucket. Therefore, the results of H_p with $X_p=x/(R.Sin\beta)$, which is a dimensionless form of distance x can be presented. The dimensionless form is a function of the bucket radius R and its deflector angle. The position x=0 represents the lip of the bucket, where the jet leave the bucket and $R.Sin\beta$ represents the length of flip bucket. Figure 11 presents the data scatter of the results for H_p against X_p along the centerline of the bucket. Based on the experimental results, the best form of relative pressure variation was found by Equation 5.

$$H_P = [-1.5X_P \exp(1+1.5X_p)]^3 \tag{5}$$

In Equation 5, pressure variation H_P along the centerline of the bucket in Equation 5 is independent of entrance Froude number F_o, but the effect of water depth ho and the geometry of the bucker (R and β) are important. At the beginning of the bucket where (X_P=-1), the pressure parameter is about (H_p=0.753). The figure shows that the effect of the bucket on pressure domain extends upstream on the chute to a distance of (X_P=-3), which should be considered as inflow boundary conditions of the bucket. For condition of (X_P<-3), the pressure parameter can be regarded as H_P=0.

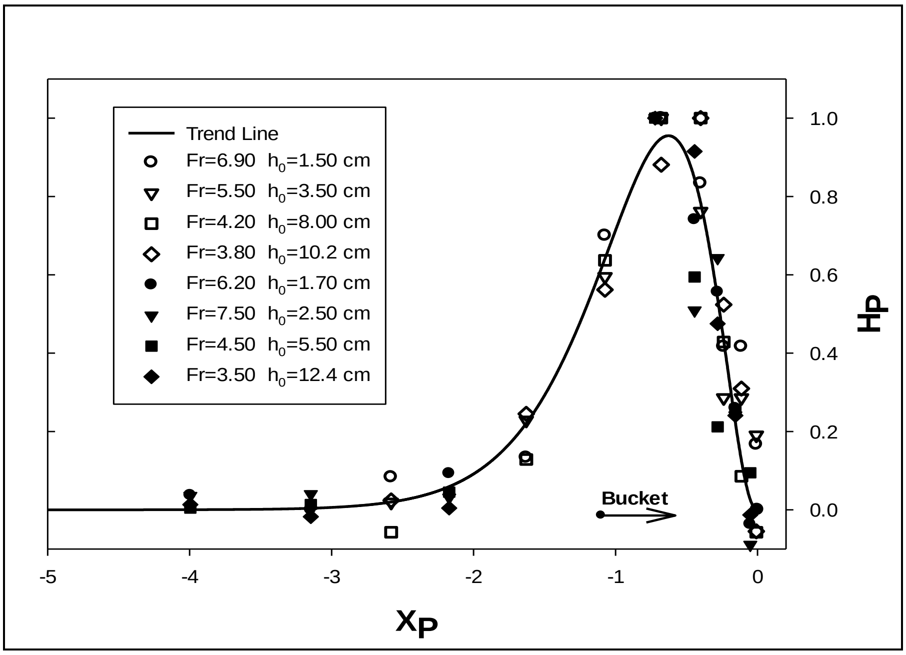

Figure 11. Variation of dynamic pressure H_P along the centerline bed of the bucket X_P (r^2=0.91)

The present information has been compared with those of previous investigations to check and validate the results. Dynamic pressure distribution based on experimental studies of Juon & Hager (2000) [17], which is independent of Froude number F_0, was expressed by the following equation:

$$H_P = [-2X_P \exp(1+2X_P)]^{2/3} \tag{6}$$

Also Heller et al. (2005) studied the dynamic pressure distribution based on physical models of different hydraulic and geometry characteristics. They introduced the following equation;

$$H_P = [-X_P \exp(1+X_P)]^{1.5} \tag{7}$$

The forms of Equations 6 and 7, which show the dynamic pressure distribution along flip buckets are in reasonable agreement with the present study as given by Equation 5. Figure 12 presents the results of the Equations 5, 6 and 7 relevant to the present study, studies of Heller et al. (2005) and Juon & Hager (2000) respectively [16, 17]. Comparison of the results shows a rough agreement.

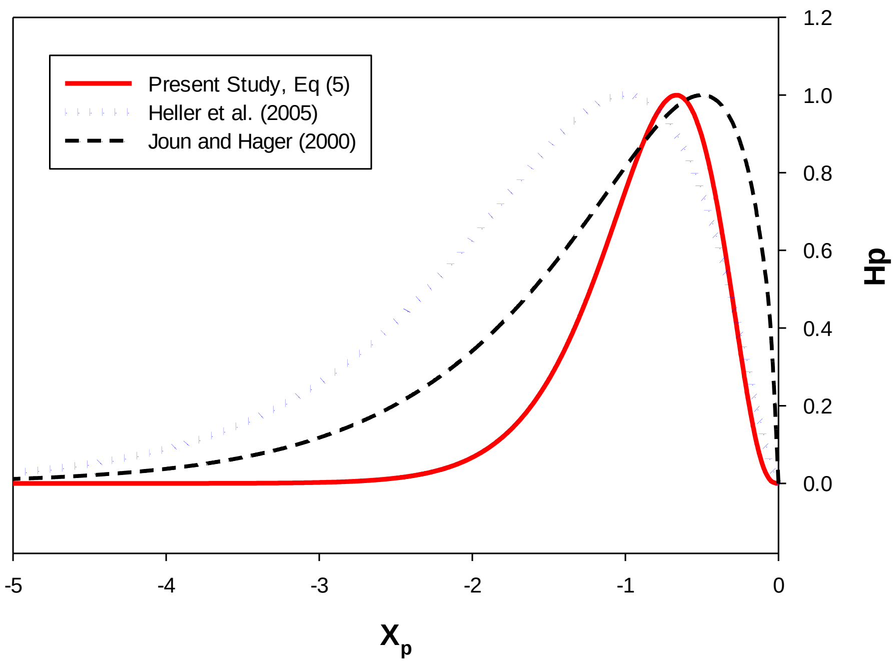

Figure 12. Comparison of the results the present study and studies of Heller et al. (2005) and Juon & Hager (2000)

The differences could be a consequence of asymmetrical flow in the flip bucket of the present study model, while Heller et al. (2005) [16] and Juon & Hager (2000) [17] studied the flip buckets at which symmetrical flow conditions exist. As a result, the present expression of pressure distribution is a reasonable suggestion for flip buckets with a high radius.

4. Conclusion

The results of this paper are based on experimental information collected from two flip buckets at Gotwand dam in Iran. The results show that upstream from the bucket, the pressure distribution starts increasing from hydrostatic values to a maximum h_{PM} and then reducing to ($h_p = -h_0$) at the end of the bucket. Based on the present results, a new expression was introduced for dynamic pressure distribution along the centerline of the bucket. Equation 5 presents the pressure distribution as a function of flow depth h_o and bucket geometry (radius R and deflector angle β). This expression is based on experiments carried out with buckets of high radius, so the result is suggested to be useful for such geometries. Therefore, by using pressure distribution graphs, the position of maximum dynamic pressure on the bed of flip buckets with a high radius can be determined. The form of this equation is in general agreement with those of previous expressions. However, the differences show the importance of geometry characteristics on pressure distribution within the flip bucket spillways.

5. Declarations

5.1. Author Contributions

Conceptualization, O.A.Y. and M.R.K.; methodology, O.A.Y. and M.R.K., and A.M.; formal analysis, O.A.Y. and M.R.K., and A.M.; writing—original draft preparation, O.A.Y. and M.R.K., and A.M.; writing—review and editing, , O.A.Y. and M.R.K., and A.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in article.

5.3. Funding

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5.4. Acknowledgements

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5.5. Institutional Review Board Statement

Not applicable.

5.6. Informed Consent Statement

Not applicable.

5.7. Declaration of Competing Interest

The authors declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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