Predictive Modeling the Free Hydraulic Jumps Pressure through Advanced Statistical Methods

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Abstract: Pressure fluctuations beneath hydraulic jumps potentially endanger the stability of stilling basins. This paper deals with the mathematical modeling of the results of laboratory-scale experiments to estimate the extreme pressures. Experiments were carried out on a smooth stilling basin underneath free hydraulic jumps downstream of an Ogee spillway. From the probability distribution of measured instantaneous pressures, pressures with different non-exceedance probabilities can be determined. It was verified that maximum pressure fluctuations, and the negative pressures, are located at the positions near the spillway toe. Also, minimum pressure fluctuations are located at the downstream of hydraulic jumps. It was possible to assess the cumulative curves of pressure data related to the characteristic points along the basin, and different Froude numbers. To benchmark the results, the dimensionless forms of statistical parameters include mean pressures ($P^*$), the standard deviations of pressure fluctuations ($\sigma^*$), pressures with different non-exceedance probabilities ($P_{k%}$), and the statistical coefficient of the probability distribution ($N_{k%}$) were assessed. It was found that an existing method can be used to interpret the present data, and pressure distribution in similar conditions, by using a new second-order fractional relationships for $\sigma^*$, and $N_{k%}$. The values of the $N_{k%}$ coefficient indicated a single mean value for each probability.

Keywords: mathematical modeling; extreme pressure; hydraulic jump; stilling basin; standard deviation of pressure fluctuations; statistical coefficient of the probability distribution

1. Introduction

In hydraulic jumps, the high-velocity of an incoming flow abruptly has an impact against a slower flow [1]. The classical hydraulic jump (CHJ) occurs on the smooth bed of stilling basins. A hydraulic jump is a phenomenon with non-deterministic characteristics, and for practical purposes, can be treated with the mathematical analysis approaches. Considering that the turbulent pressure
nature is highly random, the analysis is mainly based on mathematical methodologies. Therefore, the stochastic characteristics of the problem should be paid attention to [2,3]. This property is a function of the turbulent characteristic of the velocity and pressure field.

Knowledge of pressure fluctuations and extreme pressures allows for a better understanding of the energy dissipation process along the hydraulic jump. Notable early studies on pressure fluctuations are such as those by Bukreyev [4], Locher [5], Schiebe [6], Abdul Khader and Elango [7], Lopardo et al. [8], Lopardo [9], Tosso and Bowers [2], Farhoudi and Narayanan [10], Fiorotto and Rinaldo [11], Fiorotto and Rinaldo [12], and Armenio et al. [13].

According to Yan et al. [14], the pressure fluctuations coefficient ($C'r$) and peak frequencies of the spatial hydraulic jumps are higher than the classical jumps. Onitsuka et al. [15] found that roller oscillations affect the instantaneous flow depth and bed pressure. In addition, the instantaneous bed pressures are associated with free surface fluctuations. Lian et al. [16] stated that the fluctuating pressure spectrum in the rolling area follows the gravity similarity law. Lopardo and Romagnoli [17] and Lopardo [18] used $C'r$ coefficient values to estimate the turbulence intensities close to the stilling basin bed for low incident Froude numbers. Wang et al. [19] predicted the total pressure based on the void fraction and velocity data, and the results were in good agreement with the experimental data. Fiorotto et al. [20] studied the stability of a plunge pool lining under the fully tangency point of the curve. Novakoski et al. [30] investigated extreme pressures with different center of the vertical curve and assume values of 1% of the flow kinetic energy at the terminal dimensionless $P*_{k%}$.

Fluctuations are such as those by Bukreyev [4], Locher [5], Schiebe [6], Abdul Khader and Elango [7], Lopardo et al. [8], Lopardo [9], Tosso and Bowers [2], Farhoudi and Narayanan [10], Fiorotto and Rinaldo [11], Fiorotto and Rinaldo [12], and Armenio et al. [13].

According to Marques et al. [31], the distributions of pressures along the hydraulic jumps are not described by a normal distribution [31]. This property is a function of the turbulent characteristic of the velocity and pressure field. Such relationships allow us to organize the results of different flow discharges or Froude numbers and characterize the interest points in hydraulic jumps.
Generally, mean velocity and hydrostatic pressure are considered for designing a stilling basin. However, in the turbulent flow, the characteristics of the fluctuating fields of pressure and velocity may be more important than the mean values. Accordingly, the design of the stilling basin apron requires an assessment of the pressures acting upon the bottom of the basin to optimize concrete thickness. It is essential to study the instantaneous pressures beneath the hydraulic jump. There is little information about the pressure fluctuations, because it is quite difficult to measure the pressures underneath the hydraulic jump on the bed of stilling basins in the field [15]. Therefore, laboratory-scale experiments covering pressure fluctuations seem to be reasonable and necessary [32]. Indeed, The United States Bureau of Reclamation (USBR) has provided the general design criteria concerning the stilling basin length, assuming that the hydraulic jump is confined within the stilling basin. However, no indications are given to the different types of hydraulic jump, pressure regime, and forces on the bed of stilling basins [33].

Therefore, the main aim of the present study is to measure and provide useful information about the pressure fluctuations. To do this, the experimental results are compared with those obtained on the bed of smooth basins in the literature. Many laboratory-scale experiments were designed to simulate the flow patterns downstream of an Ogee spillway, cascading into a USBR type I stilling basin, and measuring the pressure fluctuations with a frequency of 20 Hz along the longitudinal axis of the basin. The focus of this study is the mathematical analysis of the extreme pressures distribution at the bottom of a smooth stilling basin for the incident Froude numbers (FrI) ranging from 7.12 to 9.46. New relationships will be proposed for the dimensionless standard deviation ($\sigma*_{X}$), and the statistical coefficient of the probability distribution ($N_{k%}$) to estimate the extreme pressures with different non-exceedance probabilities ($P*_{k%}$).

2. Materials and Methods

2.1. Experimental Setup

Pressure patterns along free hydraulic jumps acting on the bottom of the USBR Type I stilling basin (smooth bed) downstream of an Ogee spillway, were investigated using a laboratory model (Figure 1). The experiments were conducted in a laboratory Plexiglas-walled flume with 50 cm width, 60 cm height, and 10 m length in the hydraulic laboratory at the University of Tabriz, Iran. The flume bed was horizontal. An Ogee spillway with 70 cm height ($H$), and 61 cm length ($L$) was equipped with a Type I stilling basin according to the USBR criteria [34].

![Figure 1. Laboratory flume and the experimental setup.](image-url)
The length of the USBR Type I stilling basin \((L_b)\) was considered 200 cm [35]. The basin width \((B)\) was equal to the flume width (50 cm). The radius of the vertical curve \((R)\) at the spillway toe was 12 cm. There was a head tank with 250 cm height to stabilize the flow upstream of the spillway. A hinged weir downstream of the flume was used to control the position of the supercritical depth \((Y_1)\) at the spillway toe. The sequent depth \((Y_2)\) was measured by an ultrasonic sensor, with an operating in the range of 10 to 100 cm, and the accuracy of the nominal value the manufacture ±0.1 mm. For the classical hydraulic jump (CHJ), the most relevant parameter is the incident Froude number \((F_{ri})\). The Froude number characterizes the balance between inertial and gravitational forces. A value of \(F_{ri} > 1\) indicates the supercritical flow, and vice versa for \(F_{ri} < 1\) [36–38].

\[
F_{ri} = \frac{V_1}{\sqrt{g \times Y_1}}
\]

\[
V_1 = \sqrt{2g \times (Z - \frac{d_0}{2})}
\]

where \(V_1\) is the mean supercritical velocity; \(d_0\) is the hydraulic head upstream of the spillway crest; \(Z\) is the total water depth upstream of the spillway \((Z = H + d_0)\); and \(g\) is the gravitational acceleration. The values of \(Y_1\) are calculated using the continuity low \((Y_1 = q/V_1)\), where \(q\) is the flow discharge per unit width. Figure 2 displays some experimental parameters. Figure 3 shows the distribution of pressure taps along the centerline of the stilling basin. The flow discharge \((Q)\) was measured with an ultrasonic flowmeter. Experiments were carried out with different flow discharges in the range of 33 to 60.4 L/s. Table 1 presents the range of some experimental parameters along the hydraulic jumps.

![Figure 2. Description of some experimental parameters.](image)

![Figure 3. Distribution of pressure taps along the stilling basin.](image)
To measure the instantaneous pressure data, 25 pressure taps were installed at the bottom, along the centerline of the stilling basin. Afterward, these data were converted into electrical signals by pressure transducers via a 6-channel digital board. In this study, the transparent plastic tubes were used with an inner diameter of 3 mm, and the maximum lengths of 200 cm. The six Atek transducers (model BCT–110) had an operating range of −100 to 100 cm of the water column, with the accuracy of the nominal value the manufacture ±0.5%. The data acquisition frequency of 20 Hz with a duration of 90 seconds was used to collect 1800 sample data for each test and each pressure tap. After processing the signals using a data acquisition system, the recorded data were displayed using the 6-CH Pressure DAQ software.

### 2.2. Statistical Data Analysis

A series of methodologies to estimate hydraulic pressures under different conditions were used in the literature. Pressure with a certain non-exceedance probability ($P_{k\%}$) at the point $X$ can be estimated using Equation (3) [31]:

$$P_{k\%} = P_m + N_{k\%} \times \sigma_X$$

where $X$ is the longitudinal distance of each pressure tap from the spillway toe; $P_m$ is the mean pressure at the point $X$ (in cm of water column); $N_{k\%}$ is the dimensionless statistical coefficient of the probability distribution at the point $X$; $\sigma_X$ is the standard deviation of pressure fluctuations at the point $X$ (cm). The dimensionless mean pressure ($P_m^*$), and the dimensionless pressure with a certain probability ($P_{k\%}^*$) can be expressed as a generic function of $X^*$, and defined as follows [31]:

$$P_m^* = \frac{P_m - Y_1}{Y_2 - Y_1} = f(X^*) = f\left(\frac{X^*}{Y_2 - Y_1}\right)$$

(4)

$$P_{k\%}^* = \frac{P_{k\%} - Y_1}{Y_2 - Y_1} = f'(X^*)$$

(5)

Pressure fluctuations within the hydraulic jumps are related to energy dissipation. The dimensionless standard deviation of pressure fluctuations ($\sigma_X^*$) is defined as follows [31]:

$$\sigma_X^* = \frac{\sigma_X}{\Delta E} \times \frac{Y_2}{Y_1} = f''(X^*)$$

(6)

$$\Delta E = \left(Y_1^2 + \frac{V_1^2}{2g}\right) - \left(Y_2^2 + \frac{V_2^2}{2g}\right)$$

(7)

where $\Delta E$ is the energy head loss along the hydraulic jump (cm). This parameter depends on the incident Froude number ($Fr_1$), and the distance of the point from the jump toe. Based on Equation (3), Teixeira [26] proposed an estimation method for the extreme pressures with different probabilities ($P_{k\%}$) along free hydraulic jumps for smooth stilling basins, downstream of spillways. The method is applied to stable hydraulic jumps ($4.5 < Fr_1 < 9$), and includes the assessment of the dimensionless statistical parameters (mean pressures, standard deviation, and statistical probability distribution.

| $Q$ (L/s) | $Y_1$ (cm) | $Y_2$ (cm) | $V_1$ (m/s) | $Fr_1$ (–) |
|-----------|------------|------------|-------------|------------|
| 60.4      | 3.04       | 27.55      | 3.89        | 7.12       |
| 55.0      | 2.78       | 26.49      | 3.88        | 7.44       |
| 52.7      | 2.66       | 26.05      | 3.88        | 7.59       |
| 47.5      | 2.41       | 24.87      | 3.87        | 7.96       |
| 43.0      | 2.18       | 23.70      | 3.86        | 8.34       |
| 33.0      | 1.68       | 20.65      | 3.84        | 9.46       |
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coefficient) as a function of $X^*$ along stilling basins with the smooth bed. These parameters are defined
as follows [26]:

$$P_m^* = -0.015X^* + 0.237X^* + 0.07 \quad 0 \leq X^* \leq 8 \quad (8)$$

$$\sigma_{X}^* = -0.159X^* + 0.573X^* + 0.19 \quad 0 \leq X^* < 2.4 \quad (9)$$

$$\sigma_X^* = 0.017X^* - 0.281X^* + 1.229 \quad 2.4 \leq X^* \leq 8.25 \quad (10)$$

$$N_{k\%} = aX^* + bX^* + c \quad 0 \leq X^* \leq 8 \quad (11)$$

The parameters of $a$, $b$, and $c$ vary according to the extreme pressures with different probabilities,
and the determination coefficient ($R^2$) [39], are provided in Table 2 [26].

| $k\%$ | $a$   | $b$   | $c$   | $R^2$ |
|-------|-------|-------|-------|-------|
| 1%    | +0.0512 | -0.4480 | -1.6601 | 0.92  |
| 5%    | +0.0130 | -0.1323 | -1.3061 | 0.73  |
| 10%   | +0.0032 | -0.0450 | -1.0869 | 0.59  |
| 90%   | +0.0048 | -0.0325 | +1.2695 | 0.26  |
| 95%   | +0.0171 | -0.1393 | +1.8624 | 0.81  |
| 99%   | +0.0317 | -0.3598 | +3.3008 | 0.86  |

The spatial patterns of the skewness coefficient ($S$) may be used to highlight the flow detachment
in different zones. The sample skewness coefficient is defined as follows [40,41]:

$$S = \frac{1}{n(n-1)} \sum_{i=1}^{n} (P_i - P_m)^3 \frac{S_X^3}{f'''(X^*)} = \frac{1}{S_X^3} \sum_{i=1}^{n} (P_i - P_m)^3$$

$$S_X = \sqrt[3]{\frac{1}{n} \sum_{i=1}^{n} (P_i - P_m)^2}$$

where $P_i$ is the instantaneous pressure head at each pressure tap (in cm of water column); $S_X$ is the
sample standard deviation; and $n$ is the number of data. This value represents the pressure fluctuations concerning the mean value of the sample data. A value of $S < 0$ refers to a longer or fatter
tail on the left side of the density probability function distribution (PDF), and vice versa for $S > 0$.

The patterns of the kurtosis coefficient ($K$) in the hydraulic jump confirm the results of the
analysis of the pressure fluctuations ($\sigma^*$). The value of $K$ is a measure of the spread of data around
the mean value, characterizing the flatness of the PDF curve. A value of $K < 3$ indicates the data
distribution function is more flattened and less concentrated to the mean values compared to a
normal distribution, and vice versa for $K > 3$. The sample kurtosis coefficient is defined as [40,41]:

$$K = \left[ \frac{n(n+1)}{(n-1)(n-2)(n-3)} \times \frac{1}{S_X^4} \sum_{i=1}^{n} (P_i - P_m)^4 \right] \left[ \frac{3(n-1)^2}{(n-2)(n-3)} \right] = \frac{1}{f'''(X^*)}$$

The mathematical analysis of sample pressure data includes the calculation of the values of $P_m$,
$\sigma_x$, $P_{v%}$, and $N_{k%}$. From the analysis of the probability distribution of sample pressure data, the values
of $P_{v%}$ were determined. Then, the dimensionless form of pressure data ($P_{v%}$) was taken to compare
the results with different arrangements, obtained from a series of data with different geometries.
These parameters were analyzed longitudinally, along the stilling basin, and were made
dimensionless using Equations (4)–(6), respectively.
Based on Teixeira [26], the corresponding estimates of the dimensionless statistical parameters were determined using Equations (8)–(11) and Table 2. Afterward, the parameter of $P_m$ and $\sigma_X$ were calculated using Equations (4) and (6), respectively. Finally, the estimated values of $P_{k\%}$ was calculated using Equation (5). To optimize the pressure estimation method proposed by Teixeira [26], new relationships were developed for the parameters of $\sigma_X$ and $N_{k\%}$ as a function of $X^*$ along the stilling basin. The results of $P_{k\%}$, obtained from the analysis of the probability distribution of the experimental data were compared with the corresponding estimated values using the method by Teixeira [26], and the new optimized estimation method proposed in this study.

3. Results and Discussion

3.1. Skewness and Kurtosis Coefficient

Figures 4 and 5 present the distribution of the skewness coefficient ($S$) and kurtosis coefficient ($K$), as a function of $X^*$ for different Froude numbers. It is found that the pressure distribution along the stilling basin does not follow a normal distribution.

![Figure 4. Skewness coefficient along the stilling basin.](image)

From $S$ and $K$ charts, some characteristic points of the hydraulic jump could be defined. These are the maximum pressure fluctuations point ($X^*_{\text{max}}$), where the skewness coefficient is high, and $S_{\text{max}}$ is in the range of 0.5 to 1.5. The position of the flow detachment ($X^*_{\text{o}}$), where the skewness coefficient...
shifts from a positive value to a negative one ($S = 0$). The roller endpoint ($X'_r$) indicates the minimum skewness coefficient ($S_{min}$). The hydraulic jump endpoint ($X'_j$) is where the streamlines become parallel to the basin bed. At this position, $S = 0$ and $K = 0$.

From the previous findings concerning flow statistics, and with analysis of photographs and video recordings (not shown for shortness), four characteristic points of the hydraulic jump have been identified through the basin, and compare with the findings of Marques et al. [31]. Table 3 presents the approximate positions of $X'_{\sigma_{max}}$, $X'_d$, $X'_r$, and $X'_j$ along the stilling basin for different Froude numbers.

| Fr | $X'_{\sigma_{max}}$ | $X'_d$ | $X'_r$ | $X'_j$ |
|----|-------------------|-------|-------|-------|
| 7.12 | 1.734            | 3.98  | 5.81  | 7.71  |
| 7.44 | 1.79             | 4.11  | 6.01  | 7.97  |
| 7.59 | 1.60             | 3.95  | 6.09  | 8.08  |
| 7.96 | 1.67             | 3.89  | 5.45  | 8.41  |
| 8.34 | 1.74             | 3.83  | 5.69  | 7.55  |
| 9.46 | 2.00             | 4.09  | 5.40  | 7.51  |
| [31] | 1.75             | 4.00  | 6.00  | 8.50  |

From Table 3, the results for the smooth basin in the present study are qualitatively similar to those reported in the available literature. The values of skewness and kurtosis within the basin are different from those indicated by Marques et al. [31]. In this study, hydrodynamic pressures (measured with transducers) were used to calculate mean pressures, which display oscillatory variations. Marques et al. [31] instead used the hydrostatic pressure (i.e., from water surface profile) to approximate mean pressure. Such an assumption might be the reason for the slight differences, as explained above.

3.2. Cumulative Pressure Curves

From the pressure data with different probabilities ($P_{\%}$), the cumulative pressure curves were provided for each pressure tap with different Froude numbers. Figure 6 presents the cumulative pressure curves for $P_{\%}$ related to the characteristic points of $X'_{\sigma_{max}}$, $X'_d$, $X'_r$, and $X'_j$, respectively.
According to Figure 6, $P_{k\%}$ values increase with increasing probability ($k\%$). Minimum pressure data ($P_{\text{min}}$) correspond to the lowest probabilities ($P_{1\%}$). On the contrary, maximum pressure data ($P_{\text{max}}$) correspond to the highest probability ($P_{99\%}$). Accordingly, the maximum pressure fluctuations, and the negative pressures, are located at the positions near the spillway toe. Also, the minimum pressure fluctuations are located at the positions downstream of the hydraulic jump.

### 3.3. Proposition of New Relationships

Based on the results obtained, it was observed that the method proposed by Teixeira [26] could be optimized to be used for present data, or in similar conditions by using another relationship for...
the dimensionless standard deviation of pressure fluctuations ($\sigma^*$). Thus, a new second-order fractional relationship (rational model), as a function of the dimensionless position along the stilling basin, is introduced.

$$\sigma^*_X = \frac{a + bX^*}{1 + cX^* + dX^{2*}} \quad 0 \leq X^* \leq 7$$  \hspace{1cm} (15)

where $a = 0.3414$, $b = 0.0299$, $c = -0.4264$, and $d = 0.0994$. Figure 7 shows the corresponding scatter plot of $\sigma^*$, and fitting of Equation (15), with a determination coefficient ($R^2$) equal to 0.776.

![Figure 7](image_url)

**Figure 7.** Distribution of $\sigma^*$, including the experimental data and Equation (15).

In the present study, the values of $N_{k\%}$ with different non-exceedance probabilities are determined. Figure 8 shows the longitudinal distribution of the $N_{k\%}$ coefficient.

![Figure 8](image_url)

**Figure 8.** Distribution of the $N_{k\%}$ coefficient for different probabilities.

From the analysis of Figure 8, the constant values of the coefficient $N_{k\%}$ are developed along the jump, especially in the case of pressures with probabilities of 5%, 10%, 90%, and 95%. Therefore, depending on the probability, the values of the coefficient of $N_{k\%}$ indicate a single mean value for each probability. According to Wiest [42], there is no significant effect of the parameter of $Fr_1$ and the values of $N_{k\%}$ remain somewhat constant throughout the basin. A new second-order fractional relationship (rational model) can estimate the $N_{k\%}$ coefficient with a determination coefficient ($R^2$) equal to 0.98.

$$N_{k\%} = \frac{a + b k}{1 + c k + d k^2}$$  \hspace{1cm} (16)
where \( a = -3.1347, \ b = 6.2140, \ c = 12.9495, \) and \( d = -13.0039, \) and \( k \) is the probability value (in decimal value). Figure 9 shows the mean values of the coefficient \( N_k\% \) for each probabilities (\( k\% \)), and the proposed relationship (Equation 16).

![Figure 9. Proposed relationship for the coefficient \( N_k\% \).](image)

3.4. Comparison between Sample and Estimated Pressure Data

Figure 10 presents the distributions of \( P^*\% \) with probabilities of 1%, 5%, 10%, 90%, 95%, and 99%. Experimental data are presented as a function of \( X^* \), together with the corresponding estimates using Teixeira [26], also modified using Equation (15).

![Figure 10. Cont.](image)
Figure 10. Distributions of $P_{\%}$ with different probabilities: (a) $P_{1\%}$, (b) $P_{5\%}$, (c) $P_{10\%}$, (d) $P_{90\%}$, (e) $P_{95\%}$, and (f) $P_{99\%}$. 
Accordingly, close to the spillway toe, pressure data with low and high probability, especially for \( P_{1\%} \) and \( P_{99\%} \), have lower and higher values, with the maximum differences than \( P_{\text{m}} \). \( P_{1\%} \) data reach negative values down to \(-0.2\), at the position \( X^* \approx 2 \), indicating regions with low pressures. To evaluate the performance of the experimental and the estimated values of \( \sigma'_{X} \), some statistical performance criteria including determination coefficient \( (R^2) \) [39], root mean squared error \( (\text{RMSE}) \) [39], mean absolute error \( (\text{MAE}) \) [39], Willmott’s index of agreement \( (\text{WI}) \) [43] are provided in Table 4. As a result, the goodness of fit statistics for the estimation of \( \sigma'_{X} \) is confirmed.

Table 4. Results of the statistical performance criteria for \( \sigma'_{X} \).

| Method          | \( R^2 \) | \( \text{RMSE} \) | \( \text{MAE} \) | \( \text{WI} \) |
|-----------------|-----------|-------------------|-----------------|----------------|
| Equation (15)   | 0.776     | 0.097             | 0.075           | 0.931          |
| [26]            | 0.674     | 0.140             | 0.115           | 0.875          |

For proper performance, \( \text{RMSE} \) and \( \text{MAE} \) should be close to zero; and \( R^2 \) and \( \text{WI} \) values should be close to the unit. According to Table 4, this relationship for \( \sigma'_{X} \) provides better estimation performance as compared against Teixeira [26]. The new relationship is given in Equation (15) presents somewhat better results for \( P_{90\%} \), \( P_{95\%} \), and \( P_{99\%} \) along the stilling basin.

4. Conclusions

In this study, extreme pressures beneath hydraulic jumps inside the USBR Type I stilling basin (smooth bed) downstream of an Ogee spillway, are investigated for different incident Froude numbers ranging from 7.12 to 9.46. In summary, several conclusions are provided as follows:

1. Sample skewness \( (S) \) and kurtosis \( (K) \) coefficients indicated that the pressure distribution along the hydraulic jumps does not follow a normal distribution. Some characteristic points are the maximum pressure fluctuations point \( (X^*_{\text{max}}) \) with \( S_{\text{max}} \); the flow detachment point \( (X^*_{d}) \) with \( S \approx 0 \); the roller endpoint \( (X^*_{r}) \) with \( S_{\text{min}} \); and the hydraulic jump endpoint \( (X^*_{j}) \) with \( S \approx 0 \).

2. From the pressure data with different non-exceedance probabilities \( (P_{k\%}) \), the cumulative pressure curves are presented for \( P_{k\%} \) related to the characteristic points of \( X^*_{\text{max}} \), \( X^*_{d} \), \( X^*_{r} \), and \( X^*_{j} \), respectively. For the positions close to the spillway toe, pressures with low and high probability \( (P_{1\%} \text{ and } P_{99\%}) \), have lower and higher values, with the maximum differences than \( P_{\text{m}} \). \( P_{1\%} \) data, reach negative values down to \(-0.2\), at the position \( X^* \approx 2 \), indicating regions with low pressures.

3. From the analysis of the probability distribution of the sample data as collected by pressure transducers, pressures data of \( P_{k\%} \) can be determined.

4. Based on the results obtained, it was observed that the method proposed by Teixeira [26] could be optimized to be used for present data, or in similar conditions by using another relationship for the dimensionless standard deviation of pressure fluctuations \( (\sigma'_{X}) \), and the statistical coefficient of the probability distribution \( (N_{k\%}) \). Thus, a new second-order fractional relationship, as a function of the dimensionless position along the stilling basin \( (X^*) \), is introduced for \( \sigma'_{X} \). This relationship is valid for the dimensionless positions \( (X^*) \) in the range of 0 to 8.4. To assess the accuracy of this relationship, some performance criteria are used. For the new proposed relationship \( (\sigma'_{X}) \) in this study, the values of \( R^2 \), \( \text{RMSE} \), \( \text{MAE} \), and \( \text{WI} \) were achieved 0.776, 0.097, 0.075, and 0.931, respectively. The constant values of \( N_{k\%} \) are developed along the jump. Therefore, depending on the probability, the values of the \( N_{k\%} \) coefficient indicate a single mean value for each probability. A new second-order fractional relationship was proposed to estimate the \( N_{k\%} \) coefficient with \( R^2 = 0.98 \). The new relationships should be validated against sample data taken in similar conditions to our case study here.

5. The results contribute to enhancing the knowledge of the flow in a USBR Type I stilling basin that can be used to improve their design. This work only includes the case of free jumps. Future advancements will cover the behavior of submerged jumps with variable submergence degrees, resulting in modified pressure fields concerning those observed here for free jumps. As well, the
efficiency of blocks and sills with different sizes may be investigated. A more extensive range of
flow discharge will need to be explored. In the future, the more specific effort may be devoted
to testing other possible distributions, fitting the observed pressure fields and their use in
practice design. Also, velocity fields within the hydraulic jump may be investigated to define
the turbulent components of flow fields.

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**Notation**

The following symbols are used in this paper:

- $B$: Basin width (L)
- $Fr_1$: Incident Froude number
- $g$: Gravitational acceleration ($LT^{-2}$)
- $K$: Kurtosis coefficient
- $L$: Spillway length (L)
- $L_b$: Length of the USBR Type I stilling basin (L)
- $MAE$: Mean Absolute Error
- $N_k%$: Statistical coefficient of probability distribution at point X
- $H$: Spillway height (L)
- $P_{k%}$: Pressure with a certain non-exceedance probability (L)
- $P_{Y_k%}$: Dimensionless pressure with a certain non-exceedance probability
- $P_i$: Instantaneous pressure of each pressure tap (L)
- $P_m$: Mean pressure of each pressure tap (L)
- $P^*$: Dimensionless mean pressure of each pressure tap
- $Q$: Flow discharge ($LT^{-1}$)
- $q$: Flow discharge per unit width ($LT^{-1}$)
- $R_1$: Hydraulic radius of the incoming flow (L)
- $R^2$: Determination coefficient
- $Re_1$: Incident Reynolds number
- $RMSE$: Root Mean Squared Error
- $S$: Skewness coefficient
- $S_X$: Sample standard deviation
- $V_1$: Mean supercritical velocity ($LT^{-1}$)
- $WI$: Willmott’s index of agreement
- $X$: Distance of each pressure tap from the spillway toe (L)
- $X'$: Dimensionless distance of each pressure tap from the spillway toe, i.e., $X/(Y_2 - Y_1)$
- $X_s'$: Point of the flow detachment
- $X_j'$: Endpoint of the hydraulic jump
- $X_r'$: Endpoint of the roller
- $X_{\text{max}}'$: Point of the maximum pressure fluctuations
- $Y_1$: Supercritical depth (L)
- $Y_2$: Sequent depth (L)
- $\Delta E$: Energy head loss along the hydraulic jump (L)
- $\sigma_\epsilon$: Standard deviation of pressure fluctuations at point x (L)
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