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EXPERIMENTAL STUDY OF OBLONG BRIDGE PIER TO ESTIMATE THE AFFLUX

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Abstract

The afflux in hydraulic engineering is the maximum change of the water surface upstream of the hydraulic structure. Afflux is an important consideration to satisfy the design of the bridge. This study statistically analyzes the afflux amount. It was applied to lab experiment data which were useful for the dimensional analysis technique. As a result of the model, it has been found that the Froude number has the most significant effect on the afflux amount in the model. The contraction ratio and the angle of pier axes normal to the flow direction respectively have less effect on the afflux amount. Pearson correlation coefficient is found to be equal to +0.94 which indicates a strong positive correlation between observation and prediction values. The mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE) were calculated which were 0.008, 0.0001, and 0.011, respectively. All these values were close to zero, this indicates that the equation gave results of agreement for the forecast afflux. Also, the value of NSE was computed equal to 0.89, which was the closest to 1, which indicates that the equation was of an acceptable level performace. The coefficient of determination was found to be equal to 0.98 which also reflects a better fit for the model.

Keywords: Afflux, Contraction ratio, Froude number, Oblong pier.

1. Introduction

The afflux is increased the upstream water depth due to constructing the hydraulic structure like the bridge. The design of bridge considerations was included in the flood protection because of the afflux phenomenon [1]. The obstruction like a bridge pier caused to decrease in the nature water width and rise the water depth (upstairs normal depth) on the upstream side of the pier as shown in Fig. 1. Yarnell [2] in 1934 was the first researcher of field afflux, also concluded the importance of the afflux study in river training and bridge design. This author studied the afflux as the function of the Froude number downstream and the contraction ratio based on the different piers shapes. In 1960, Bradley [3] concluded the Froude number and contraction ratio was an effect on afflux value estimates.

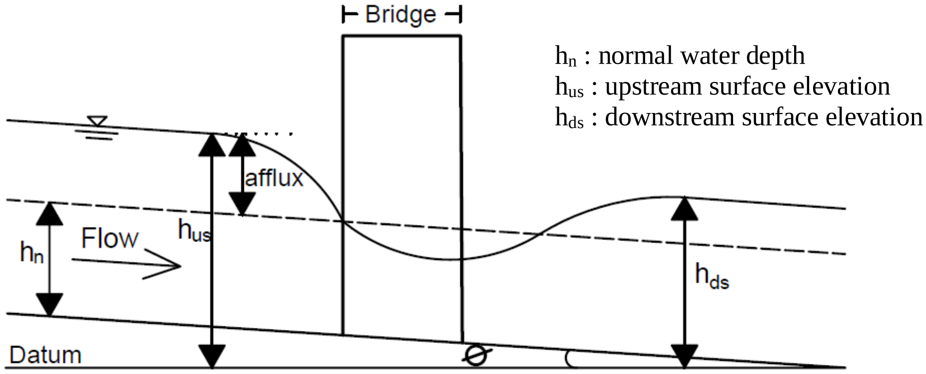


Fig. 1. Side view of Afflux phenomenon [4].

A new equation was developed from the statistical analysis to estimate the afflux amount derived from the observations of the experiments of the rectangular bridge pier. The new effects of the axes of a pier to flow direction were included to find the afflux values on the lab beside other parameters such as the upstream Froude number and contraction ratio [5].

Bridge afflux in compound channels was studied by Seckin et al. [6]. An empirical formula was recognized to determine afflux at the arch and straight deck bridge site for low flow conditions in the composite channel. Moreover, the researcher found that the Froude number, depth of flow, and blockage ratio on the downstream side are the primary factors that affect the afflux in the compound channel. The prediction afflux at high flows condition by using the ISIS bridge methods was studied via Atabay [7]. The experimental data of this research were used to investigate the reliability and performance of two ISIS bridge methods which included the HR ARCH and USBPR bridges methods. In ISIS bridge methods, the Bernoulli loss unit was used to predict the water level elevation with a bridge structure in place. The comparison between the results of these methods and experimental data computed at various floodplain roughness conditions of two stages channel. These models included arch bridge model with a single opening semicircular (ASOSC), arch bridge model with a multiple opening semicircular (AMOSC), elliptic arch bridge model with a single opening (ASOE), and straight deck bridge model (with and without piers) with a single opening [7].

The lattice Boltzmann method (LBM) was used to predict the afflux depended on the two-dimensions nonlinear equations of shallow water (LABSWE), this method attempted to bridges with a single or multi-span of free water surface without introducing additional empirical coefficients [4]. The LBM investigated three configuration parameters that affected a single-span bridge included eccentricity, skewness, and blockage ratio while a multi-span bridge was influenced by the skewness and shape of the pier. The afflux and flow distribution across the section and around the obstruction were estimated by the LABSWE.

Hadi and Ardiclioglu [8] used the HEC-RAS package and experimental for determination the afflux to four different opening ratios ranged from 0.3 to 0.9 without effect the orientation angle of piers. One dimensional model software via HEC-RAS and ISIS was utilized to estimate the afflux values as a full scale at a site after calibration the model by experimental data [9].

Ghodsian and Shafieefar [10] conducted an experimental study of the effect of bridge piers shapes on afflux value and found that a rectangular pier has a greater afflux amount than a circular pier. These two researchers arrived at a laboratory equation that calculated the afflux around the piers by entering the shape effect and contraction ratio without introducing the angle of inclination of the pier with the flow axis. The afflux was calculated for semi-circular piers to the range of discharges from 0.0075 m^3/s to 0.035 m^3/s, the different contraction ratios (0.91, 0.82 and 0.73) were studied, but the researchers neglected the effect of the angle of orientation with the direction of flow (skewness angle) on the afflux, i.e., the piers were placed at the same angle for all runs [11].

Shamkhi and Salim [12] used the same discharges in the previous study (0.0075 m^3/s to 0.035 m^3/s) to measure the effect of the difference in the angle of orientation of the piers with the direction of flow on the afflux, where the angles were 0, 15, 45, and 60 degrees, but the researchers utilized a single contraction ratio, meaning that the number of piers for all experiments is the same.

Biological neural networks have certain performance characteristics in common with the artificial neural network which is the information (data) processing system. Mathematical models of human perception or neurobiology have been used to develop artificial neural networks. The artificial neural networks commonly used are to form and develop a relationship between input and output, whether linear or non-linear, by forming two test and training groups. The artificial neural network steps have been taken the following assumptions: the first step is the neurons that process information in many simple elements. The next step is to pass connection links between neurons as signals. The third assumption is that there is a weight for each connection link, which is multiplied by the signal transferred. The last step in the hypotheses is to determine the output of the signal, as it depends on its application that each neuron which is a non-linear activation function in addition to the neuron's value and weight [13].

In the field of Hydraulic/Afflux due to constriction, there have been multiple studies that have developed equations to estimate the amount of afflux. Furthermore, these studies presented different statistical equations to compute the afflux upstream of rectangular and circular bridge piers. However, none of these studies deals with oblong bridge piers.

One of these configurations is the stability of the bridge. The oblong pier is one of the most stable bridge piers [14]. This shape is more efficient to resist floods and earthquakes [12]. Therefore, many designers start using the oblong pier when they design bridges. This new shape must be studied in detail. One of the important issues with this new design is afflux. So, we need to develop a statistical model to predict the amount of afflux upstream of the oblong bridge pier.

This paper will cover this issue to be an important tool, which can be used by designers in the field of bridge design. Different shapes of piers, different contraction ratios (depending on the number of piers, which ranges from 2 to 8), and the orientation angles of the piers with the axis of flow (skewness angle) were a new addition to develop a more comprehensive equation of afflux. The overlap between the use of different angles and the ratio of contraction is new in this study because bridges are usually in situ have a percentage of contraction with different angles of the piers with the direction of flow.

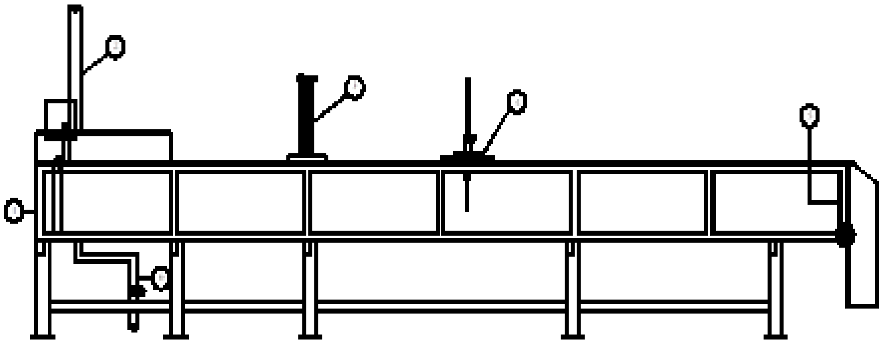
2. Methods

The experiments in this study were performed to study the amount of afflux prediction of the oblong pier in the laboratory flume. This flume is glass fiber with steel stiffeners which dimensions consisted of a length of 6.6 m, a width of 0.4 m, and a depth of 0.4 m as illustrated in Figs. 2(a) and (b).

Different diameters of the piers were used; these achieved using different numbers ranging from 2 to 8 piers with a diameter of 2.25 cm, to form the different percentage of the contraction ratio (σ) values. The piers were fixed at the mid of the flume length. The screens provided the upstream of the flume to constrain the turbulent flow within tolerable limits. The centrifugal pump was used beside the upstream flume to supply the water from the underground tank with a constant head. The triangular sharp-crested weir at the end upstream of the flume was used to measure the discharge. The gauge point with an accuracy of $\pm$0.01 mm was utilized to compute the water depth.

There is a thirty-eight run of lab tests performed in this study to compute the amount of afflux. The ranges of discharge were from 3.98 l/s to 6 l/s, the water depth was from 3.5 cm to 12.12 cm, the number of used piers were 2, 4, 6, and 8 while the normal angle of the pier to flow direction change from 65 to 90 degree as shown in Fig. 3. The calibration between the measured discharge and actual discharge was attempted prior to the estimated afflux as shown in Fig. 4. It should be noted that the actual discharge was measured using the method of volume and time (stopwatch). As for the theoretical discharge (measured), it was measured using the tool (weir). This figure summarized by correcting the discharge values that were less than 0.67 l/s (670 cm^3/s) while the discharge values that were higher than this limit are taken as they are [15].

The experiment method was with the following steps, the first of which is to install the piers (according to their condition from the angle and the specified number) in the middle of the flume, then secondly, the specific discharge was opened through the valve in the upstream, the particular flow is determined by the weir. The third step was that after the discharge stabilized, the upstream depth of water from the piers is measured by the point gauge at a distance to ensure that the depth and flow are not affected by the narrowing of the piers. The fourth step was to measure the depth of the water at the piers. Thus, the afflux was measured by subtracting these two depths.



1- Inlet tank, 2- Supplied pipe, 3- Gate, 4- Point gauge, 5- Tailgate, 6- Drain.

(a). Side view of lab flume [15].

(b). Three-dimensional flume lab.

Fig. 2. Laboratory flume details

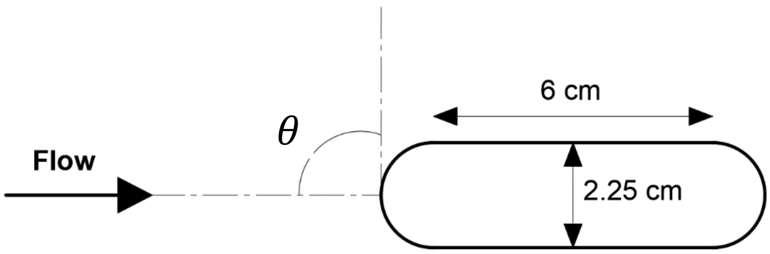


Fig. 3. Details of the pier dimensions and the skew angle with the flow.

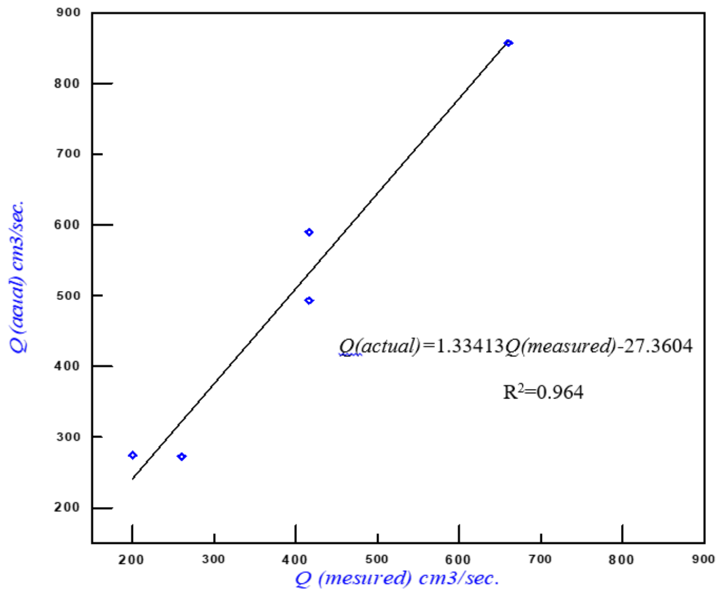


Fig. 4. Discharge calibration curve [15].

Afflux due to the oblong bridge pier is a complex problem. The number of variables encountered in the problem is large. In order to simplify the study, dimensional analysis theory (Rayleigh method) is used to study the variables and minimize their number by putting them in dimensionless parameters. The variables of an oblong pier in Fig. 1. were utilized to derive the parameters which affect afflux values. The upstream normal depth of pier h, approach velocity of flow V, contraction ratio σ (σ =1- piers width “b” / flume width “B”), acceleration due to gravity g, angle of pier axes normal to the flow direction θ, and shape of pier represented by k, water density ρ, water viscosity μ are the parameters that influence of afflux values Δh. In this study, the presence of sediments at the bottom of the flume was neglected, although sediments were found in natural rivers. The reason for this is the mechanism of flow around the piers in natural rivers that leads to the formation of pits due to the scour around it, which leads to a relative decrease in the depth of the afflux as a result of the pit formed around the pier. Therefore, afflux measurement in the absence of sediments is most valuable due to the local scour phenomenon. These parameters were used as below:

$$\Delta h = f\,(h, V, \rho, \mu, g, \sigma, \theta, k) \quad (1)$$

Using the MLT terms to obtain the dimensionless group as illustrated; the values of $\sigma, \theta,$ and k are dimensionless.

$$M^0T^0L^1 = c\,(L)^a \left(\frac{L}{T}\right)^b \left(\frac{M}{L^3}\right)^c \left(\frac{M}{LT}\right)^d \left(\frac{L}{T^2}\right)^e \quad (2)$$

$$\text{M: } 0 = c + d \;\Rightarrow\; c = -d \quad (3)$$

$$\text{L: } 1 = a + b - 3c - d + e \quad (4)$$

$$\text{T: } 0 = -b - d - 2e \;\Rightarrow\; b = -d - 2e \quad (5)$$

Substituting Eqs. (3) and (5) into Eq. (4) obtained:

$$a = 1 - d + e \tag{6}$$

$$\Delta h = c.(h)^{1-d+e}.(V)^{-d-2e}.(\rho)^{-d}.(\mu)^{d}.(g)^{e} \tag{7}$$

$$\Delta h = c.h.\left(\frac{\mu}{h.V.\rho}\right)^{d}.\left(\frac{h.g}{V^2}\right)^{e} \tag{8}$$

where $1/\mathrm{Re} = \frac{\mu}{h.V.\rho}$ and $1/\mathrm{Fr}^2 = \frac{h.g}{V^2}$.

So the afflux value as Eq. (1) depended on the following parameters:

$$\Delta h = f(h, \mathrm{Re}, \mathrm{Fr}, \sigma, \theta, k) \tag{9}$$

Murphy [16] recommended the effect of Reynolds Number can be neglected due to the secondary importance (The flow in the laboratory flume was fully turbulent). In addition that, the piers with rectangular (oblong) shape were utilized to predict the lab afflux, the parameter of shape eliminated from Eq. (9) to give:

$$\Delta h/h = \mathrm{f}(\mathrm{Fr}, \sigma, \theta) \tag{10}$$

$$\frac{\Delta h}{h} = C_1 \times Fr^{C_2} \times \sigma^{C_3} \times \theta^{C_4} \tag{11}$$

Each run of the thirty-eighth was the sequence of measurements for each parameter by the following procedure begins with installing the piers in the mid of the flume at a certain angle, so the theta (θ) was determined. As for the contraction ratio (σ), it was calculated by computed the width of all the piers (b) fixed to the flume and the width of the channel (B=0.4 m), by applying the following law (1-b/B). After the water flow had stabilized, it was measured by the weir at the upstream, the presence of the depth, and the dimensions of the flume, the velocity was set via dividing the discharge by the cross-sectional area of the flow, so that the Froude number (Fr) can be measured by the known law ($V/\sqrt{gh}$). Finally, the afflux (Δh) was measured by subtracting the depth of the water at the pies and another place where the contraction effect did not appear.

The measurement procedure was summarized by using a point gauge with the end of the needle attached to the base at the top of the flume, and it can slide left and right. The needle was connected to the end of a graduated rod with an accuracy of 0.01 mm. Where a bolt fixed at the top released, the graduated rod was lowered until the needle touched the water surface that required to measure. Afflux measurement was done by measuring the highest point of water depth at the upstream of the piers minus the normal depth when the flow had stabilized.

All details of the laboratory experiments were presented in Table A-1 as illustrated in Appendix A. It should be noted that the conditions for conducting the experiments were generally similar since the flume was located inside a laboratory. In addition to the above, a slight change in temperature occurs, a slight change in the viscosity and density of the water does not affect the accuracy of the results.

The importance of each parameter (Froude number, sigma, and theta) of the factors of the equation extracted by the dimensional analysis method and its effect on afflux can be estimated. By using the statistical program SPSS software, the importance of each factor can be extracted.

3. Results and Discussion

The relationship between the Froude number (Fr) and observation afflux to water depth (Δh/h) for different cases of contraction ratio *σ* (1-b/B, b = all piers width for each run and B = the width of flume that always equal to 0.4 m) was drawn as seen in Fig. 5. It is obvious that by increasing the Froude number value water level increases along with the upstream, which means afflux is directly proportional to the Froude number value for different values of sigma. This figure also exposed the inversely proportional between the sigma and afflux (i.e. increase the sigma caused to decrease the afflux). This value was chosen for the Froude number (Fr = 0.1515) because it covered all the variables of sigma and theta, and the purpose was to view the increase or decrease of the afflux. Increasing the theta (*θ*) causes to decrease in the afflux value (i.e. inversely propositional) for the specific value of the Froude number as shown in Fig. 6. Also, it shows the same conclusion that the correlation between the sigma and afflux was inversely proportional. The increase or decrease of the afflux matched the intuitive effects on it, so the runs in the appendix can be utilized to create a statistical equation. The relationships between the sigma, theta, and the Froude Number with observation afflux were predicted depended on the experiments from the lab.

The importance weight of each parameter of Eq. (11) based on experimental results was computed by Neural Network techniques using the statistical program. The percentage of independent variables' importance of all experimental data (which illustrated in appendix) were computed in Table 1 which illustrated that the Froude number has a significant effect on afflux value then sigma and theta respectively. In other meaning, the approach velocity and the water depth were the most effective parameters on the afflux value based on the Froude number law ($V/\sqrt{gh}$) with constant gravity acceleration (g). The importance value of the Froude number equal to 0.44 means that any change of the magnitude of the Froude number has a more pronounced effect than the same change if it was at the theta angle since the magnitude of importance (0.18) was less.

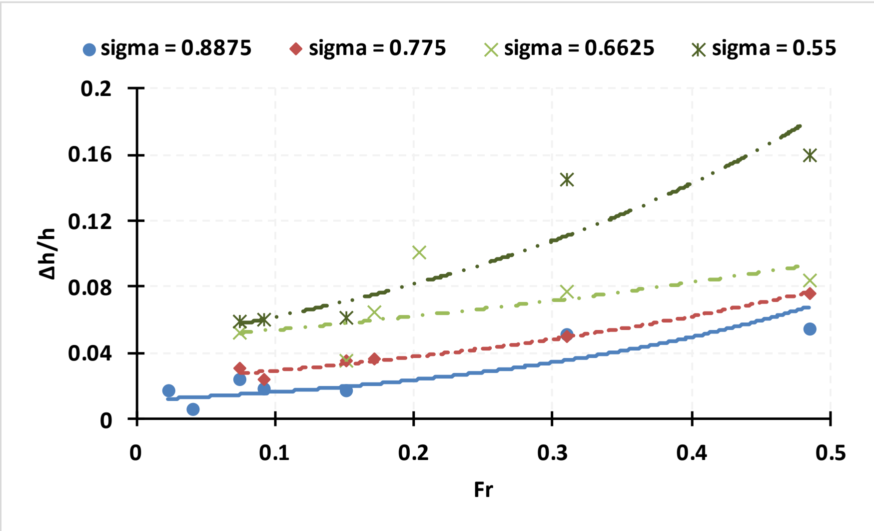


Fig. 5. Relation of Δh/h with Fr for different values of sigma (*σ*), when *θ*=90.

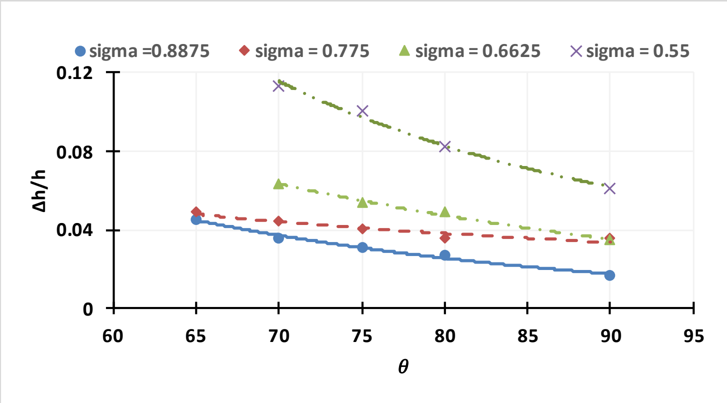


Fig. 6. Relation of Δh/h with θ for different values of sigma (σ), when Fr = 0.1515.

Table 1. The percentage of independent variables importance.

	Importance	Normalized Importance
Fr	0.437	100.0%
Sigma	0.381	87.3%
Theta	0.182	41.8%

The statistical software was applied to estimate the constant-coefficient (C_1, C_2, C_3 and C_4) in Eq. (11). Equation (12) was concluded for this software as below by using user-specified regression, least squares method:

$$\frac{\Delta h}{h} = 3.748 \times Fr^{0.567} \times \sigma^{-2.367} \times \theta^{-0.924} \quad (12)$$

There are matching between Figs. 5 and 6 with the power sign of constant coefficients of Eq. (5) which was represented the afflux was directly proportional to the Froude number and inverse proportional with sigma and theta values. The observation and prediction values of afflux with the coefficient of determination were illustrated in Fig. 7. The Pearson correlation coefficient is equal to +0.94 that concludes a very strong correlation between the observation and prediction values of afflux.

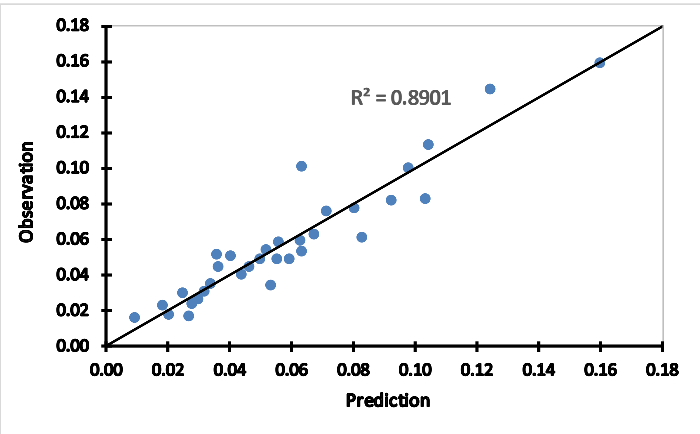


Fig. 7. The observation and prediction values of afflux.

There are several tests to ensure that the method of least squares is valid to estimate the afflux prediction and Eq. (12) is correct. The first condition is the normality test of residual as the hypothesis:

The null hypothesis H_o: The distribution of residual is normality. The alternative hypothesis H_1: The distribution of residual is no normality.

Using the statistical techniques to test the hypothesis above as seen in Fig. 8. which depended on the Kolmogorov-Smirnov Test for Normality. The *p*-value (> 0.15) is more than the value of alpha (default = 0.05), so the null hypothesis H_0 is accepted (The distribution of residual is normality). The homogeneity of residuals was tested as shown in Fig. 9. which appeared is none uniform distribution. To make more sure that the extracted equation statistically was accepted to estimate the value of the afflux. So the mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE) were calculated and values were 0.008, 0.0001, and 0.011, respectively. The three values were close to zero and this indicates that the equation was given agreement results of prediction afflux. In addition, the acceptable level of the equation can be estimated by extracting the value of Nash-Sutcliffe efficiency (NSE), which value was equal to 0.89. This NSE value was between 0 and 1, It was closer to 1, which indicates that the equation was acceptable performance.

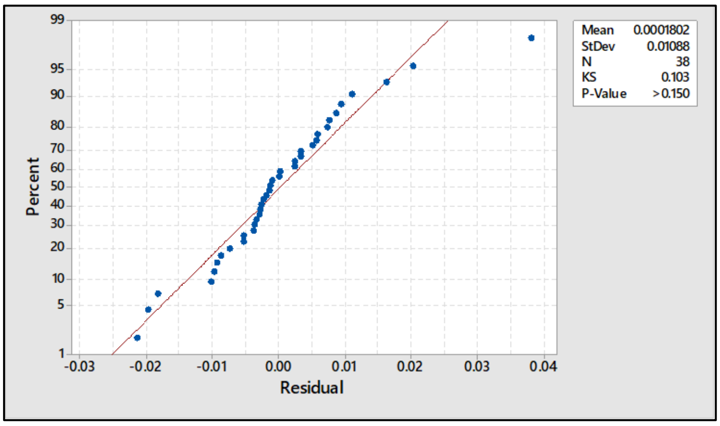


Fig. 8. Normality test of residual values.

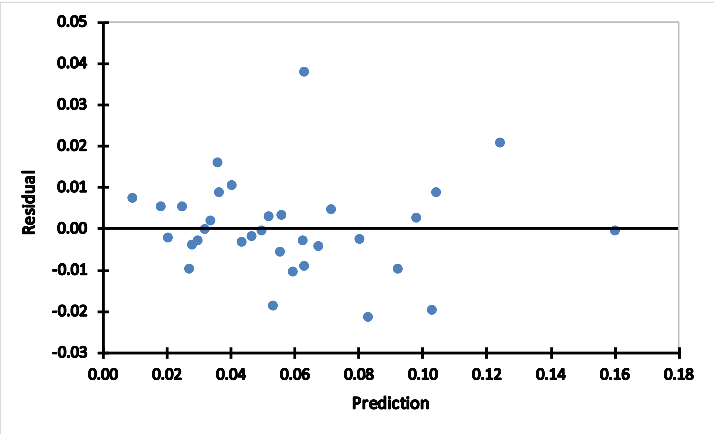


Fig. 9. The prediction versus residual distribution.

Also, the final step of verification by using some of the data that is not used to develop the model equation. The coefficient of determination (R^2) of verification shows a strong correlation between the observation and prediction data as illustrated in Fig. 10.

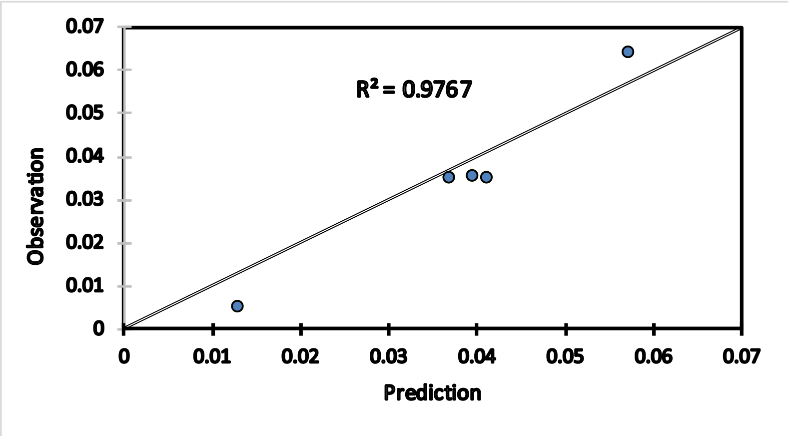


Fig. 10. The verification of prediction afflux values.

4. Conclusions and Recommendation

Afflux upstream of a rectangular bridge pier was studied in the paper that concluded as follows:

- There is an agreement between the results from observation lab data and the statistical model results.
- The Neural Network techniques concluded the Froude Number to have more effect on the value of afflux upstream of pier than the contraction ratio σ and the angle of pier axes normal to the flow direction θ respectively, so the results show that the approach velocity and water depth have the most influence on the afflux values
- A statistical model has been built to estimate the amount of afflux. It also found that the Pearson correlation coefficient is equal to +0.94, which, reflects a strong correlation between the observation and prediction, values of afflux.
- The mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE) were calculated, the values were 0.008, 0.0001, and 0.011, respectively. The three values were close to zero indicating that the equation used to forecast the afflux gave agreement results.
- The value of Nash-Sutcliffe efficiency (NSE) was calculated to be 0.89, which was to the nearest 1. This value indicates that the extracted equation was of an acceptable level performance.
- The verification of the equation shows a strong value of the coefficient of determination equal to 0.98.

Additional experiments will improve the correlation coefficient. Furthermore, the experiments could involve trying a wide range of discharge values. This would improve the statistical model results.

Nomenclatures

Fr	Upstream Froude Number
g	Acceleration due to gravity, m/s^2
h_n	Normal water depth, m
h_{us}	Upstream surface elevation, m
h_{ds}	Downstream surface elevation, m
h	The upstream normal depth of pier, m
Δh	Afflux values, m
k	Shape of pier
V	Approach velocity of flow, m
Re	Reynolds Number

Greek Symbols

θ	The angle of pier axes normal to the flow direction
μ	Water viscosity
σ	Contraction ratio
ρ	Water density

Abbreviations

p-value	Statistical significance testing value

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Appendix A

Table A-1 Details of laboratory experiments.

Run No.	Q	h	Fr	σ	θ	Afflux (Δh)
	l/s	m	-	-	degree	cm
1	0.8316	0.0950	0.0228	0.8875	90	1.5
2	3.9766	0.1212	0.0752	0.8875	90	1.6
3	3.9766	0.1058	0.0923	0.8875	90	1.5
4	3.9766	0.0760	0.1515	0.8875	90	2
5	3.9766	0.0471	0.3104	0.8875	90	7
6	3.9766	0.0350	0.4846	0.8875	90	8
7	3.9766	0.1212	0.0752	0.775	90	2
8	3.9766	0.1058	0.0923	0.775	90	2
9	3.9766	0.0471	0.3104	0.775	90	7
10	3.9766	0.0350	0.4846	0.775	90	11
11	3.9766	0.1212	0.0752	0.6625	90	3.5
12	3.9766	0.0760	0.1515	0.6625	90	4
13	3.9766	0.0471	0.3104	0.6625	90	11
14	3.9766	0.0350	0.4846	0.6625	90	12
15	3.9766	0.1212	0.0752	0.55	90	4
16	3.9766	0.1058	0.0923	0.55	90	5
17	3.9766	0.0760	0.1515	0.55	90	7
18	3.9766	0.0471	0.3104	0.55	90	20
19	3.9766	0.0350	0.4846	0.55	90	22
20	3.9766	0.0760	0.1515	0.8875	80	3
21	3.9766	0.0760	0.1515	0.8875	75	3.5
22	3.9766	0.0760	0.1515	0.8875	70	4
23	3.9766	0.0760	0.1515	0.8875	65	5
24	3.9766	0.0760	0.1515	0.775	75	4.5
25	3.9766	0.0760	0.1515	0.775	70	5
26	3.9766	0.0760	0.1515	0.775	65	5.5
27	3.9766	0.0760	0.1515	0.6625	80	5.5
28	3.9766	0.0760	0.1515	0.6625	75	6
29	3.9766	0.0760	0.1515	0.6625	70	7
30	3.9766	0.0760	0.1515	0.55	80	9
31	3.9766	0.0760	0.1515	0.55	75	10.5
32	3.9766	0.0760	0.1515	0.55	70	12
33	6	0.0820	0.2039	0.6625	90	10
34	4.543	0.0760	0.1714	0.775	90	4
35	4.543	0.0760	0.1714	0.6625	90	7
36	1.4627	0.0925	0.0415	0.8875	90	0.5
37	3.9766	0.0760	0.1515	0.775	90	4
38	3.9766	0.0760	0.1515	0.775	80	4