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Prediction of Scour Downstream Regulators Using ANNs

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Abstract Regulators is considered one of the main irrigation structures that is used for many purposes. One of the main purposes of regulators is to measure and control the discharge of rivers; also it is used to control the water levels and to generate power. Scour is an inevitable problem that occurs downstream regulators. Different researchers tried to predict scour hole downstream regulators, but their results always gave scour dimensions less than that actually occur. Scour was studied either on solid bed by means of velocity distribution or on movable bed by investigating the topography of the scour hole. In this paper, the scour hole was studied on movable bed by using a new technique rather than the traditional techniques used by other researchers. Due to the complex and unexpected behaviour of water as well as sediment movement downstream regulators, a Back-Propagation Neural Network (BPN) model was developed to predict the dimensions of the scour hole formed downstream regulators, in order to overcome the problem of exclusive and non-linear relationships. A Three layered feed forward neural network using Levenberg-Marquardt algorithm was formulated. The inputs to the (BPN) model were obtained through an extensive experimental program carried out on a trapezoidal channel 0.0001 bed slope. The study covers free and submerged hydraulic jump conditions in both symmetrical and asymmetrical under-gated regulations. It was found that the scour hole dimensions in case of submerged hydraulic jump is always greater than the free one, also the scour hole dimensions in asymmetrical operation is greater than symmetrical one. From the comparison between the experimental results and the predicted ones by the (BPN) model, we found that the scour hole dimensions can be efficiently predicted using (BPN).

Keywords Back-propagation Neural Network (BPN), Prediction Models, Regulators, Scour

1. Introduction

Most of the existing hydraulic structures such as regulators consist of multi-vents and most problems that occur downstream of such structures are due to the wrong operation of the multi-vents leading to unpredicted velocity distribution which in turn leads to unexpected scour patterns. Due to the existence of piers and abutments as parts of these structures, the flow issuing out of their gates behaves as flow in sudden expanding stilling basin when all gates are working together. Mostly, symmetric flow in sudden expanding stilling basins resulted in symmetric scour downstream of the basin and vice versa[1],[2]. The study of scour hole downstream control structures was studied either by velocity distribution or by investigating the topography of the scour hole on movable bed located after an arbitrary length of rigid floor. Velocity distribution over rigid bed upstream of the movable bed helps in depicting the nature of scour patterns downstream of the rigid bed. Studies on velocity distribution downstream of single vent regulatorsmay be found in[3],[4]. Studies of local scour of alluvial channels near rigid aprons which are based upon the examination of topography of scour holes produced by different hydraulic conditions was studied by different researchers among them[5],[6]. The flow downstream irrigation structures may be free or submerged; however, the submerged flow is the mostly encountered in the field. Many studies are available in the literature about the submerged flow and submerged hydraulic jump characteristics under numerous flow conditions[7]–[13]. Most of these investigations concluded that the length of the roller of submerged hydraulic jump is longer than that of free one; consequently the scour length may be largely extended in case of submerged hydraulic jump rather than free one. Attempts to verify these results were investigated in this study.

The study of scour downstream irrigation structures using (ANNs) was studied by many researchers. The underlying reason for the overall superiority of the (ANNs) models to the existing and the proposed formulas is attributed to its ability to capture the highly non-linear relations among the

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different parameters. Application of (ANNs) in the field of Hydraulic and Water Engineering could be found in[14]–[17]. Applications of (ANNs) to predict scour downstream hydraulic structures such as culvert is presented by[18] and to predict scour at bridge abutment was presented by[19]. Prediction of hydraulic jump characteristics using (ANNs) was introduced by[14],[20]. Application of (ANNs) to predict discharge below sluice gates under free and submerged flow was investigated by[21], and to predict discharge below gate with sill[22]. Detailed information on the subject of (ANNs) may be found in[23]. The aforementioned methods do not give a reliable formula to predict scour hole dimensions downstream regulators to cover all possible ranges, where all formulae obtained from the previous studies give scour hole dimensions less than the actual one.

A new technique was introduced in this paper to study the scour hole dimensions downstream hydraulic structures over movable bed both experimentally and theoretically, where all the previous studies on movable bed, predict the scour length by assuming an arbitrary length of rigid apron L, less than the expected scour length, L_s, and they consider that the length of the scour hole L_s, is equal to the length of the rigid floor plus the length of the scour hole formed in the downstream; $L_s = L + X_s$. Actually, this technique gives smaller scour lengths than the actual ones.

This paper solves that problem by extending the arbitrary length of the rigid floor, L by the same value of the length of the scour hole X_s formed in the downstream until no scour hole is allowed to form. For this purpose, three millimetres steel sheets with the same channel width and different lengths according to the length of the scour hole X_s, were used to extend the rigid apron length behind the model of the regulators.

The study covers different flow scenarios that might occur in the field, where free and submerged hydraulic jumps were investigated, and also both symmetrical and asymmetrical operations were taken into consideration. Based on the previous obtained data from the experimental program, a (BPN) model was created to predict the scour hole dimensions downstream 3-vents regulators. The model is a three layered feed forward neural network which uses Levenberg-Marquardt algorithm. An optimization technique was investigated to the (BPN) model to obtain the perfect prediction model for simulating the scour process. Trial and error method was used to obtain the best network parameters for the best performance of the model. The results of the (BPN) model showed a good agreement with the experimental results with high correlation coefficient.

The study reveals that the minimum length of rigid apron to prevent scour L_s is always greater than the sum of the lengths of the arbitrary rigid apron and that of scour hole formed behind it; ($L+X_s$) for the same flow conditions. Also the scour hole dimensions is found to be greater in case of submerged hydraulic jump than free one, furthermore the dimensions increase in case of asymmetrical operation than symmetrical one.

2. Dimensional Analysis

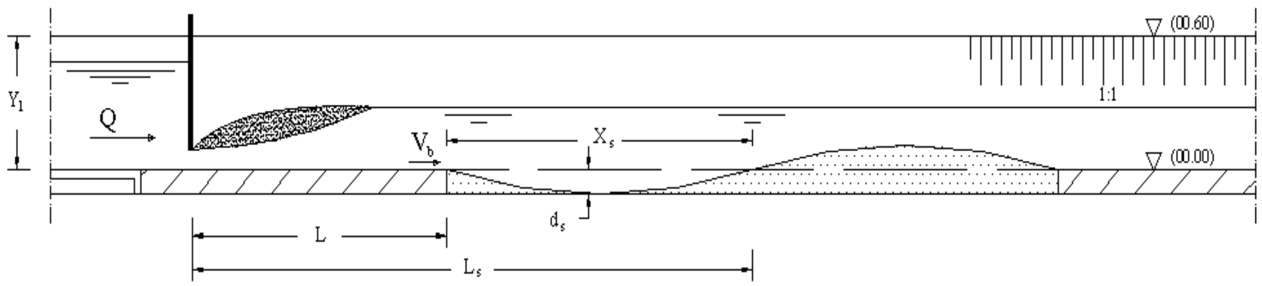

Figure 1. Definition sketch showing the geometry of the scour hole and the different parameters considered in this study

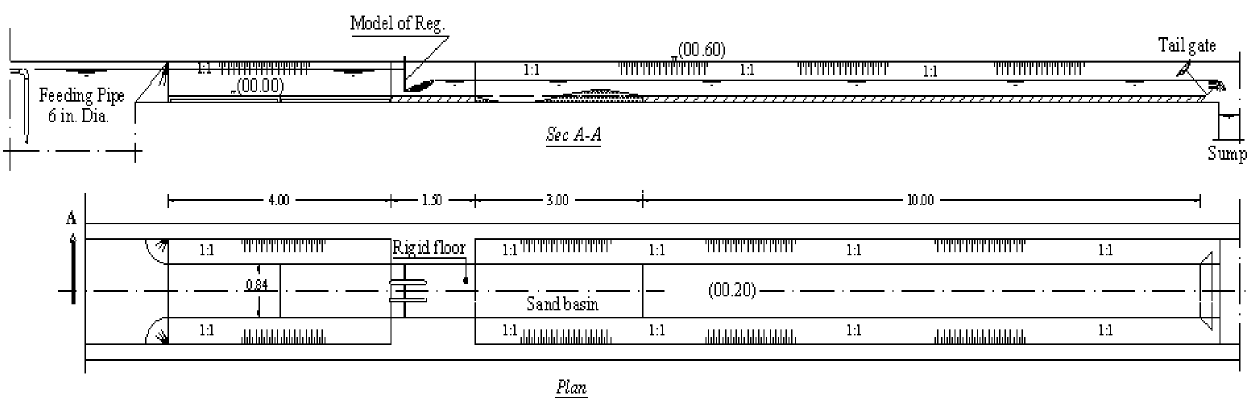

Figure 2. Different parts of the experimental channel

In the analysis of the problem of scour downstream regulators, different parameters should be considered. Fig. 1 represents these parameters. L_s : minimum length of rigid apron to prevent scour measured from the gates (no scour hole is allowed), L : arbitrary length of rigid apron behind the gates, X_s : length of scour hole formed downstream the rigid apron having length (L), d_s : maximum scour hole depth, d_{50} : median diameter of the bed material located in the sand basin, g : gravitational acceleration, Q : discharge passed through the gates of the regulators, V_b : bed velocity at the end of the solid floor, S: longitudinal bed slope of the channel, Y_1 : upstream water depth, Y_2 : downstream water depth, μ : absolute viscosity of water, ρ_s : soil particles density and ρ : water density. Limited variations of these dimensions appear not to have any considerable effect of flow pattern[24],[25]. On the other hand, in case of mild slope; which is the case of the most Egyptian irrigation channels, the channel bed slope has weightless effect on the scour reach downstream of sluice gates[24]. So, in this study the longitudinal bed slope will be kept constant at 0.0001. On the other hand the effect of changing the size of bed material was investigated by many researchers. They concluded that the force exerted by the flow on the sediment particles to be lifted up and move is higher in case of large sediment size than small ones, consequently as the particle size increases the scour hole dimensions slightly decrease. So, the bed material size in the sand basin will be kept constant at 0.502 mm.

From the aforementioned presentation, the geometry of the scour hole represented by L_s or $(L + X_s)$ and d_s may depend upon the other remaining parameters as follows:

$$L_s \, or (L + X_s) or \, d_s = \phi_1 (Y_1, Y_2, Q, V_b, \rho, \mu, g) \quad (1)$$

Using π – Theorem, it yields;

$$\frac{L_s}{Y_2} or \frac{(L + X_s)}{Y_2} or \frac{d_s}{Y_2} = \phi_2 \left(\frac{Y_1}{Y_2}, \frac{V_b^2}{gY_2}, \frac{\rho V_b Y_2}{\mu}, \frac{Q}{Y_2^2 V_b} \right) \quad (2)$$

$$\frac{L_s}{Y_2} or \frac{(L + X_s)}{Y_2} or \frac{d_s}{Y_2} = \phi_3 \left(\frac{H}{Y_2}, F_e, R_e, \tau^* \right) \quad (3)$$

in which H, is the working head defined as the difference between the upstream and downstream water levels $(Y_1 - Y_2)$, V_b^2 / gY_2 is the Froude number, $\rho V_b Y_2 / \mu$ is the Reynolds' number, $\tau^* = \tau_b / \tau_c$ is the shields parameter, τ_b is the bed shear stress calculated at the separation point between the solid floor and the sand basin, it may be given as[24]:

$$\tau_b = \rho f V_b^2 / 8 \quad (4)$$

in which f is the friction coefficient obtained from the following formula[24];

$$1/\sqrt{f} = 2.00 \log(12.6 Y_2 / d_{50}) \quad (5)$$

and τ_c, is the critical shear stress obtained from shields' diagram[26], it may be calculated from the following formula:

$$\tau_c = (\gamma_s - \gamma_w) \varepsilon d_{50} \quad (6)$$

where γ_s, is the specific weight of soil particles, γ_w is the specific weight of water and ε is a parameter ranges from 0.04 to 0.1[26].

In free surface model studies, the viscous force does not affect the flow field and therefore R_e, in (3) may be dropped[27],[28]. In open channel flow[29] found that the gravity starts to affect the flow resistance when F_e equals to 2.49.

Reference[30] revealed that the importance of Froude number appears only when roll waves develop to form a state of unstable flow. Hence, (3) reduces to;

$$\frac{L_s}{Y_2} or \frac{(L + X_s)}{Y_2} or \frac{d_s}{Y_2} = \phi_4 \left(\frac{H}{Y_2}, \tau^* \right) \quad (7)$$

3. Materials and Methods

3.1. Channel

The investigations reported herein were conducted in a sloped-bed channel of trapezoidal cross section as shown in Fig. 2. Generally the channel has a bed width of 0.84 m and a depth of 0.6 m. It consists of four parts, the first part is trapezoidal with side slope 1:1 and total length of 4.00m, the second part is rectangular which has a length of 1.50 m. This part is the testing section where the model of regulators was installed in it. The third part is trapezoidal with side slopes 1:1 and length of 3.00 m. In this part sand with 0.502 mm diameter was placed with a depth of 20 cm. The fourth part has a trapezoidal cross section with side slopes 1:1 and a sufficient length of 10.00 m to create a uniform flow in the downstream. The uniform water flow depth could be adapted by means of a tailgate installed at the channel end. The flow rate was regulated by a gate valve located on the feeding pipeline and was measured by a calibrated V-notch. Water depths and bed levels were measured by point-gauges. The velocity was measured by a calibrated Pitot-tube.

3.2. Model

Three sluice gates and two intermediate piers were formed a model of three-vents regulator as shown in Fig. 2. Each gate has 0.24 m width, 0.60 m height and 6 mm thickness with sharp edge. The pier is 60 mm in width, 0.60 m total length, 0.38 m of them behind the gates and it has two 7x8 mm groves to hold the gates in a vertical position. The gates can be lifted and lowered to give the desired under-gated opening height that permits to form free or submerged hydraulic jump conditions on the solid bed.

3.3. Experimental Method

The experimental program which was carried out to investigate the scour hole dimensions downstream regulators under different flow conditions was divided into two categories:

i. First category: In this category, the experiments were performed to determine the total length of the scour hole as the previous studies, where the length of the scour hole equal to the sum of the arbitrary length of the solid floor and the length of scour hole formed in the downstream ($L+X_s$). The experimental procedures were as follows:

1)- The three gates were lifted up to give a certain opening-height, h (case of symmetrical regulation).

2)- The downstream portion of the channel was filled with water to a certain limit.

3)- The run started with low flow rate, and then gradually the flow rate was increased to the required one.

4)- The downstream water depth was adjusted by the tail gate till the formation of free hydraulic jump just behind the gates and between the piers (case of free jump) or the formation of a submerged hydraulic jump between the piers (case of submerged jump) with maximum upstream water depth Y_1 not more than 2.2 times the downstream water depth Y_2[31].

5)- After 4 hours run time[32], the water depths upstream Y_1 and downstream the gates Y_2, the discharge Q, and the velocity near the bed at the end of rigid floor were recorded. Then the flow was stopped and the scour hole length X_s and its depth d_s were measured.

6)- The gates opening or the discharge was changed and the procedures from 1 to 5 were repeated.

7)- For asymmetric flow, the left hand side vent of the model of the regulator was closed and the same procedures from 1 to 6 were repeated.

ii. Second category: In this category, tests were performed to find out the minimum scour length where no tail erosion is encountered on the erodible basin. Three millimeters steel sheets with 0.84 m wide and different lengths were used to extend the rigid apron length behind the model of the regulator as shown in Fig. 3.

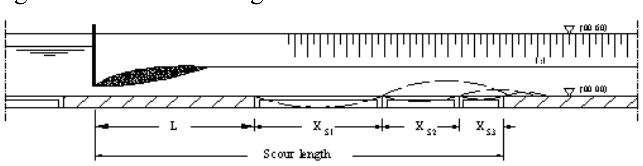

Figure 3. Definition sketch showing the technique used to extend the rigid floor to prevent the formation of the scour hole

The total length of the scour hole in this case is as follows:

$$L_s = L + \sum_{k=1}^{n} X_s \tag{8}$$

where L is the arbitrary length of the rigid floor, and the term $\sum_{k=1}^{n} X_s$, represents the summation of all possible lengths that can be added to the arbitrary length of the rigid floor to prevent scour. The test procedures in this case were as follows:

1)- In symmetrical case and for both the formation of free or submerged hydraulic jump downstream the gates of the regulator, the discharge Q, downstream water depth Y_2, and consequently upstream water depth Y_1 were chosen.

2)- The rigid apron length behind the model was extended gradually; the recorded erosion rate was decreasing till there was no erosion encountered. Then, the minimum length of rigid apron measured from the end of the gates to the beginning of the erodible bed L_s was recorded to the nearest 10 mm. At this moment the velocity near the bed at the end of rigid apron was measured.

3)- The gates opening or the discharge was changed, and then steps 1 and 2 were repeated.

4)- For case of asymmetrical under-gated regulation, the left hand side vent of the model of the regulator was closed and same procedures from 1 to 3 were repeated.

3.4. Back-Propagation Neural Network Model (BPN)

A typical three-layered neural network with an input layer (I), a hidden layer (H) and an output layer (O), Fig. 4 is adopted in this study. Each layer consists of several neurons and the layers are interconnected by sets of correlation weights. The neurons receive inputs from the initial inputs or from the interconnections and produce output by the transformation using an adequate non-linear transfer function in the hidden layer and linear function in the output layer. The transfer functions used in this research are the sigmoid transfer function in the hidden layer expressed by $f(x) = 1/1 + e^{-x}$, it has a characteristics of $d_f / d_x = f(x)[1 - f(x)]$ and the purelin transfer function in the output layer. The training process of a neural network is essentially executed through a series of patterns. In the learning process, the interconnecting weights are adjusted within input and output values. The model parameters were optimized by Levenberg and Marquardt algorithm, which is one of the most common and successful back-propagation algorithms. To make the algorithm fast and easy to learn the non-linearity between the inputs and outputs, it is important to use some processing functions with the inputs as well as the outputs. These processing functions are built-in functions in MATLAB's Neural Network Toolbox. A MATLAB's processing functions were applied to normalize the input and output values, which is a requirement of Levenberg–Marquardt back-propagation algorithm calculation process for (ANNs) modeling.

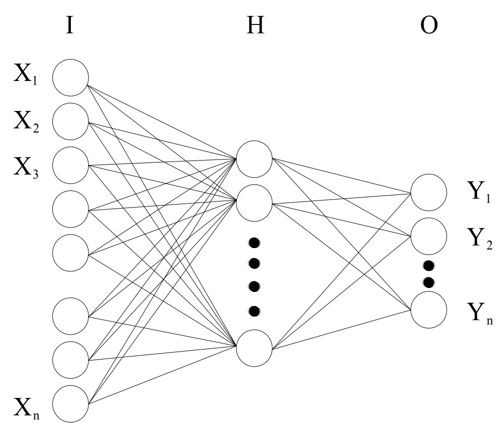

Figure 4. Structure of an artificial neural network

Based on the dimensional analysis that has been carried out in sec. II, the input data to the (BPN) model will be the

Shields' parameter and the dimensionless head difference between upstream and downstream $(\tau^*, H/Y_2)$ in all possible cases (free, submerged, symmetrical, and asymmetrical case), on the other hand, the output from the model will be the dimensionless minimum length of rigid apron downstream the gates to prevent scour L_s/Y_2, the dimensionless summation of the lengths of rigid apron and that of scour hole formed behind it $(L+X_s)/Y_2$ and the dimensionless scour hole depth d_s/Y_2.

The (BPN) is the most representative learning model for the artificial neural network. The procedure of the BPN is that the error at the output layer propagates backward to the input layer through the hidden layer in the network to obtain the final desired outputs. The gradient descent method is utilized to calculate the weights of the network and to adjust the weights of interconnections to minimize the output error. The error function at the output neuron is the least mean square (LMS) error function defined as:

$$mse = \frac{1}{Q}\sum_{k=1}^{Q} E(k)^2 = \frac{1}{Q}\sum_{k=1}^{Q}(T(k)-Y(k))^2 \quad (9)$$

where E(k) is the error value, T(k) is the target output value and Y(k) is the current network output. The gradient descent algorithm adapts the weights according to the gradient error which is given by:

$$\Delta W_{ij} = -\eta \frac{\partial E}{\partial W_{ij}} \quad (10)$$

where η is the learning rate and the general form of the $\partial E/\partial W_{ij}$ term is expressed by the following form:

$$\frac{\partial E}{\partial W_{ij}} = -\delta_j^n A_i^{n-1} \quad (11)$$

Substituting Eq. (11) into Eq. (10) yields the gradient error

$$\Delta W_{ij} = \eta \delta_j^n A_i^{n-1} \quad (12)$$

in which A_i^{n-1} is the output value of sub-layer related to the connective weight (W_{ij}) and δ_j^n is the error signal, which is computed based on whether or not neuron j is in the output layer. If neuron j is one of the output neurons, then:

$$\delta_j = (T_j - Y_j)Y_j(1-Y_j) \quad (13)$$

If neuron j is the neuron of the hidden layer, then:

$$\delta_j = (\sum_j \delta_j (W_{kj})_{hj})H_h(1-H_h) \quad (14)$$

where H_h is the value of the hidden layer.

Finally, the value of weight of inter-connective neuron can be expressed as:

$$W_{ij}^m = W_{ij}^{m-1} + \Delta W_{ij}^m = W_{ij}^{m-1} + \eta \delta_j^n A_i^{n-1} \quad (15)$$

To accelerate the convergence of the error in the learning procedure, the momentum term α is included into (15).

$$W_{ij}^m = W_{ij}^{m-1} + \eta \delta_j^n A_i^{n-1} + \alpha \Delta W_{ij}^{m-1} \quad (16)$$

To estimate the accuracy of the proposed methodology, the Correlation Coefficient was used as the agreement indexes:

$$R = \frac{\sum_{k=1}^{n}(y_k - \bar{y}_k)(\hat{y}_k - \bar{\hat{y}}_k)}{\sqrt{\sum_{k=1}^{n}(y_k - \bar{y}_k)^2 \sum_{k=1}^{n}(\hat{y}_k - \bar{\hat{y}}_k)^2}} \quad (17)$$

where $\hat{y}_k$ is the observed value, y_k is the predicted value, $\bar{y}_k$ is the mean value of predictions, $\bar{\hat{y}}_k$ is the mean value of observations and n is the number of data points.

The previous steps which was performed to obtain the most appropriate (BPN) model is shown summarized in the flow chart in Fig. 5.

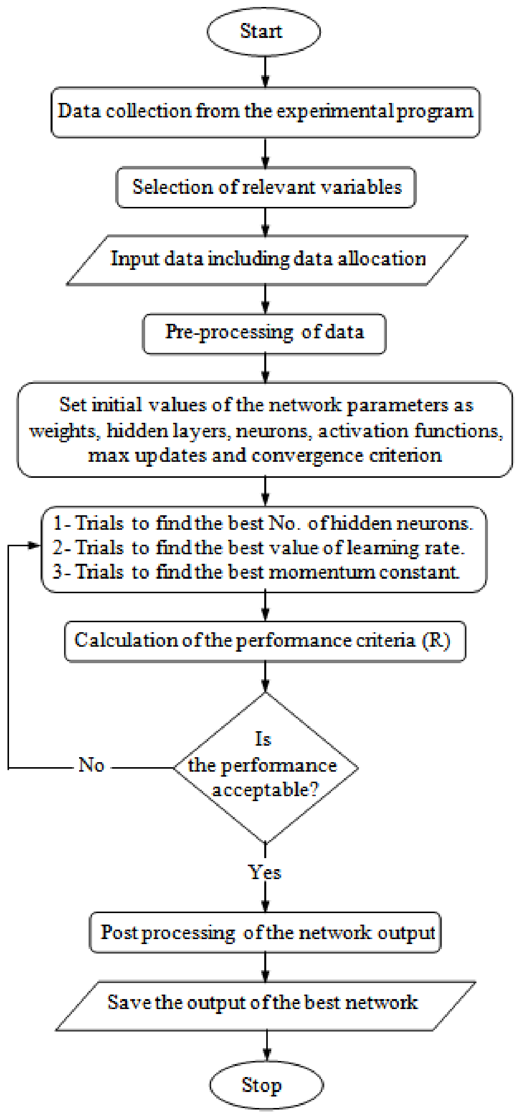

Figure 5. Flowchart showing the basic steps of building the (BPN) model for the present study

4. Application and Discussion of Results

4.1. Data Analysis Based on the Experimental Point of View

Most investigations on local scour of alluvial channels near rigid aprons were based upon the examination of the topography of scour holes produced by different hydraulic conditions[33]–[36]. In the present study, another approach is considered, where the scour reach will be represented by both the minimum floor length L_s to prevent scour behind the model of three vents regulator or by the sum of an arbitrary length ($L < L_s$) besides the length of scour hole X_s. For this reason the analysis of the scour length in the following sections will be represented either by L_s or by ($L + X_s$).

At first, it is important to perform a preliminary check for the experimental results to take decision about the case (free or submerged case) that will be used as an input to the (BPN) model. Fig. 6 indicates the relationship between the dimensionless head difference, H/Y_2, and the dimensionless scour length L_s/Y_2 or $(L+X_s)/Y_2$ for the free and submerged cases.

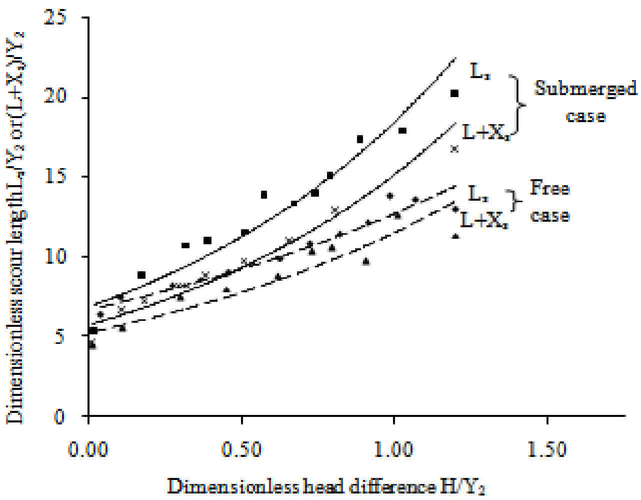

Figure 6. Variation of Ls/Y2 or (L+Xs)/Y2 with H/Y2 for free and submerged under-gated regulations (symmetrical case)

It is clear that the submerged scour length L_s/Y_2 or $(L+X_s)/Y_2$ is always greater than the free one. These results are in agreement of other researchers who concluded that the length of the roller of submerged hydraulic jump is longer than that of free one and as a result, the produced scour length in case of submerged hydraulic jump is greater than the length of free one[7],[34],[37]. For this reason the proposed (BPN) model will be constructed only in the submerged case and all results will be shown in case of submerged hydraulic jump.

One of the famous formulas to predict scour length downstream control structures such as regulators based on the acting head is the Bligh's formula[38].

$$L_s = C\sqrt{H} \tag{18}$$

where L_s is the floor length behind the piers of regulator to prevent scour, H is the maximum working head difference between upstream and downstream water levels and C is a parameter depending on the bed materials (takes the values from 8-10 for silt and sand range). For this reason we will derive some relationships from this study to predict scour length based on the acting head. The relation between the scour length L_s/Y_2 or $(L+X_s)/Y_2$ and the acting head H/Y_2, is given in the following forms (For free and submerged symmetrical case):

In case of submerged hydraulic jump:

$$L_s / Y_2 = 6.92 \exp^{0.98(H/Y_2)} \tag{19}$$

$$(L + X_s) / Y_2 = 5.77 \exp^{0.96(H/Y_2)} \tag{20}$$

In case of free hydraulic jump:

$$L_s / Y_2 = 6.76 \exp^{0.63(H/Y_2)} \tag{21}$$

$$(L + X_s) / Y_2 = 5.22 \exp^{0.79(H/Y_2)} \tag{22}$$

One can distinguish that the scour length L_s with no scour hole allowed is always greater than the summation of the arbitrary length of the rigid floor plus the length of the scour hole ($L+X_s$). Also the submerged scour length is always greater than the free one. From this point it is recommended for practical purposes, to increase the scour length obtained from the examination of the topography of the erodible bed by the previous studies by an average value of 7.50% and 23% in case of free and submerged cases respectively.

Also the relationship between the dimensionless head difference H/Y_2 and the dimensionless scour length L_s/Y_2 or $(L+X_s)/Y_2$ in case of symmetrical and asymmetrical under-gated submerged regulation is shown plotted in Fig. 7.

We can verify that the scour length generated in case of asymmetrical under-gated regulation is always greater than that of symmetrical one. The correlation of L_s/Y_2 or $(L+X_s)/Y_2$ and the acting head H/Y_2, is given in the following forms (submerged asymmetrical case):

$$L_s / Y_2 = 8.69 \exp^{0.83(H/Y_2)} \tag{23}$$

$$(L + X_s) / Y_2 = 7.04 \exp^{0.88(H/Y_2)} \tag{24}$$

Comparing (19), and (23) it is important to increase the submerged scour length obtained in symmetrical under-gated regulation by an average value of 5% to cover the unexpected asymmetrical case.

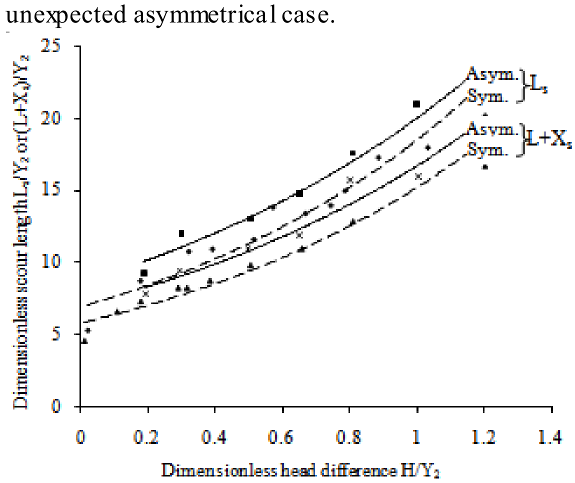

Figure 7. Variation of Ls/Y2 or (L+Xs)/Y2 with H/Y2 for symmetrical and asymmetrical under-gated regulations (submerged case)

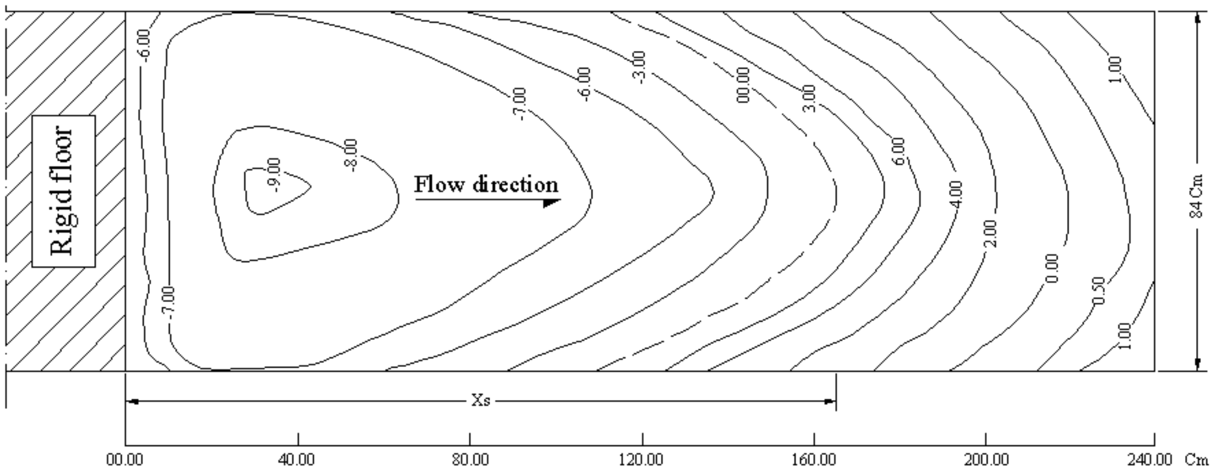

Figure 8. Contour lines of the movable bed showing the scour hole profile behind the rigid floor of length, L = 0.60 m for symmetrical under-gated regulation (H = 0.16 m, Q = 21 Lit./s and hg =32mm)

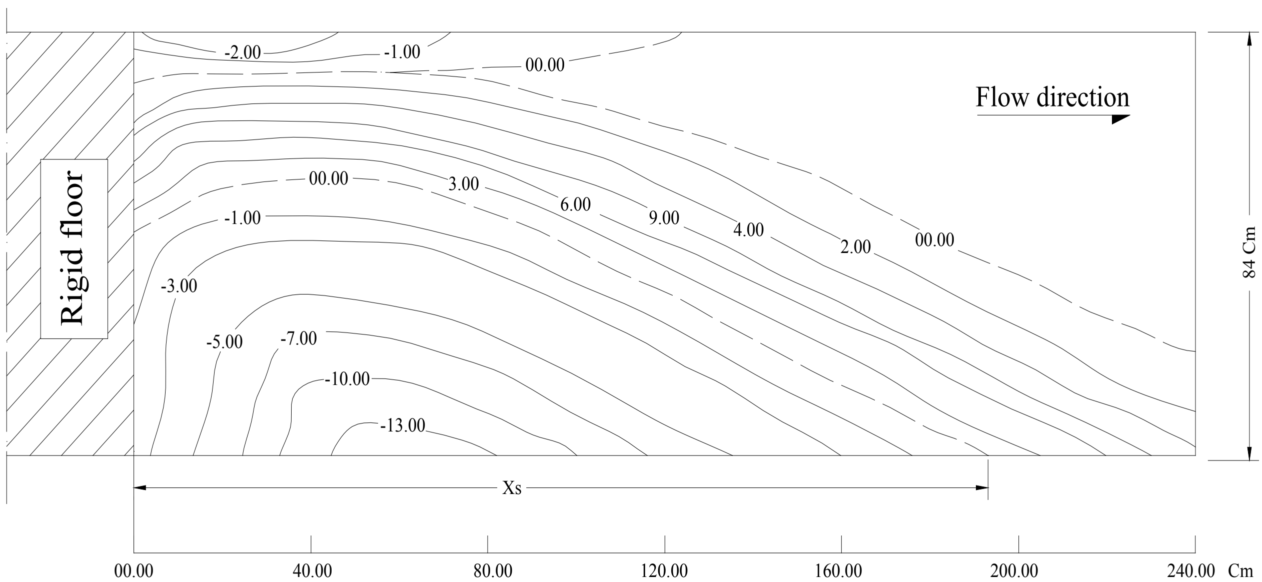

Figure 9. Contour lines of the movable bed showing the scour hole profile behind rigid floor of length, L = 0.60 m for asymmetrical under-gated regulation (H = 0.16, Q = 21 Lit./s and hg =43mm)

In practice, flow downstream regulators may be asymmetric under-gated regulation when: 1) One or many vents are working while the adjacent are closed because of the periodic maintenance. 2) There is a lock besides the regulator for navigation purposes. 3) The sub-structure needs restoration works. From this point it is essential to investigate the effect of asymmetrical regulation on the scour reach downstream regulators. The left hand side vent of the model in the direction of flow was closed completely while the others were working.

Shown in Figs. 8 and 9 the plotting of the contour lines of the developed scour hole for both symmetrical and asymmetrical under-gated regulations respectively. Keeping the ratio H/Y_2, the discharge Q, and the floor length, L constant, we can observe that for asymmetrical regulation the scour hole depth and length are greater than those measured for symmetrical regulation. Also, the soil particles are accumulated forming a hill downstream of the closed gate. This may due to the increase of the amount of turbulence with the formed reverse currents.

4.2. Determination of the Optimized (BPN) Prediction Model

To predict scour hole dimensions in all possible cases that have been mentioned earlier, an optimization procedures were implemented to illustrate the applicability of the (BPN) model with different structures to tide predictions. A (BPN) used here is a non-linear system in which parameters affect each other. This section discusses how the neural network structure affects the performance of the forecasting model, which includes the number of neurons in the hidden layer n, the learning rate η, and the momentum constant α. The number of the training iterations (Epochs) will be kept constant at 1000 iterations. The input and output pairs of data to the (BPN) model were divided randomly using a suitable function, where we customize the divide process between the training data sets (70%) and test or validation data sets (30%). Several results have been obtained, but we chose the trial which gave high correlation coefficient especially in the test data test, because these data represents the testing of new data to the network that has never seen before.

The number of neurons in the hidden layer was selected to vary from 2 to 16 with a constant step of 2 neurons. Table 1 shows the values of correlation coefficient for various neurons structures with constant learning rate of 0.05, constant momentum of 0.4 and constant epochs of 1000. It shows that the quality of simulations improved when the number of neurons is 6 neurons. Thus, the number of neurons in the hidden layer is recommended to be 6 neurons because of its satisfactory prediction performance, where the correlation coefficient for all and test data sets equal to 0.9873 and 0.9702 respectively.

Table 1. Performance of the (BPN) model associated with different values of neurons with constant learning rate and momentum

Hidden neurons	Learning rate	Momentum	Epochs	Correlation Coefficient	
				All	Test
4	0.05	0.4	1000	0.9059	0.7626
6	0.05	0.4	1000	0.9873	0.9702
8	0.05	0.4	1000	0.9847	0.9673
10	0.05	0.4	1000	0.9766	0.9530
12	0.05	0.4	1000	0.9550	0.8675
14	0.05	0.4	1000	0.9379	0.7339
16	0.05	0.4	1000	0.9758	0.9370

On the other hand, the values of the learning rate η will significantly affect the convergence of neural network learning algorithm, so it is recommended to try different values of the learning rate. Table 2 indicates the different values of the correlation coefficient with the optimum number of neurons obtained from the previous step, (n = 6) with variable learning rate. It is clear that the suitable learning rate is 0.05 with the optimum 6 neurons obtained from the previous step.

Table 2. Performance of the (BPN) model associated with different learning rates with constant NUMBER OF NEURONS, AND MOMENTUM

Hidden neurons	Learning rate	Momentum	Epochs	Correlation Coefficient	
				All	Test
6	0.01	0.4	1000	0.9679	0.8400
6	0.05	0.4	1000	0.9873	0.9702
6	0.1	0.4	1000	0.9674	0.9348
6	0.3	0.4	1000	0.8563	0.6412
6	0.5	0.4	1000	0.9619	0.9337
6	0.7	0.4	1000	0.8662	0.5515
6	0.9	0.4	1000	0.9234	0.8932

The momentum factor α may accelerate the convergence of the training process, so it is preferable to change the momentum constant to obtain the most suitable (BPN) prediction model. Table 3, shows the different momentum values that have been used in this study to obtain the perfect (BPN) model. It indicates that the efficiency of the model is better when the momentum constant is equal to 0.7, where the best performance is achieved with a correlation coefficient of 0.9886 for all data sets and 0.9836 for test data set.

Table 3. Performance of the (BPN) model associated with different momentums with constant number of neurons, and learning rates

Hidden neurons	Learning rate	Momentum	Epochs	Correlation Coefficient	
				All	Test
6	0.05	0.01	1000	0.9744	0.9325
6	0.05	0.05	1000	0.9723	0.9231
6	0.05	0.1	1000	0.9504	0.8220
6	0.05	0.3	1000	0.9584	0.9312
6	0.05	0.5	1000	0.9398	0.6761
6	0.05	0.7	1000	0.9886	0.9836
6	0.05	0.9	1000	0.9650	0.6313

The results of the best (BPN) model obtained from the optimization technique that was used in the previous step for all data sets as well as test data sets are shown plotted in Fig^{s}. 10 and 11. We can see that the model is capable to predict the scour hole dimensions effectively. As we mentioned before that training of the (ANNs) needs processing functions to accelerate the learning process and to make the network stable. In that case we used a function that transfers all input and output data to be within the range -1 and +1. For this reason the results shown in Figs. 10 and 11 are within these two values.

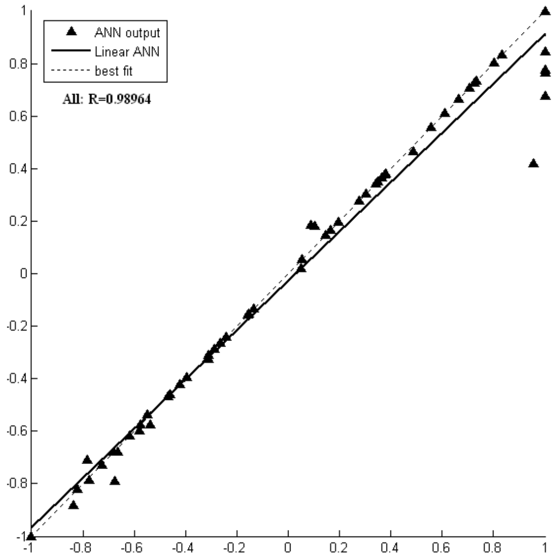

Figure 10. The BPN model predictions for all data sets

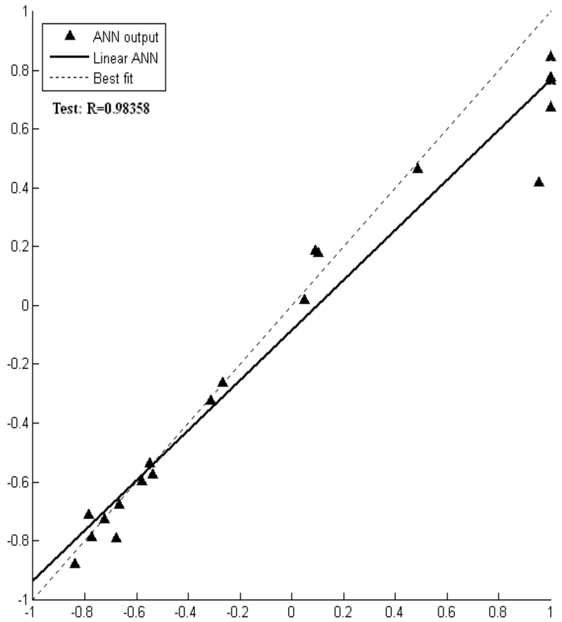

Figure 11. The BPN model predictions for test data sets

4.3. Scour Predictions in Case of Symmetrical Operation

The results of the optimum (BPN) model, obtained earlier with 6 neurons in the hidden layer, learning rate of 0.05 and momentum constant of 0.7, were used to predict the scour hole length in case of symmetrical operation. Shown in Fig. 12, the relation between the dimensionless scour length L_s/Y_2 or $(L+X_s)/Y_2$ and the dimensionless acting head H/Y_2.

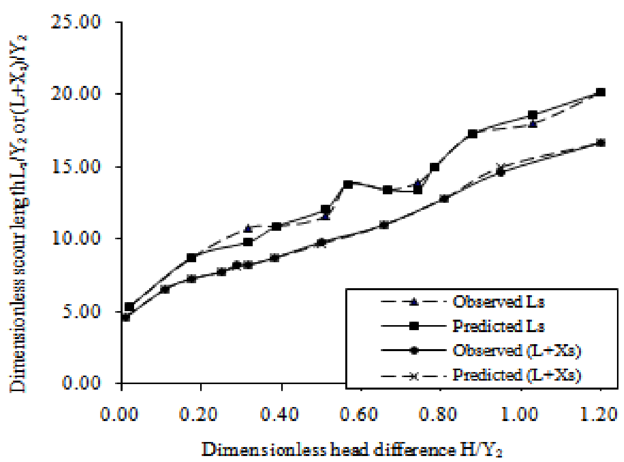

Figure 12. Comparison between the forecasting results of the BPN model and that of experimental observations for the influence of the head difference on the scour length L_s or $(L+X_s)$

We can see that the increase of the acting head is associated with an increase in the values of scour length. This can be explained by; the increase in the working head H will be resulted in an increase in the flow kinetic energy and consequently the erosion forces due to the shooting flow issuing from under the gates. Furthermore we can notice that the scour length L_s investigated by this research, is greater than $(L+X_s)$ investigated by traditional methods, and that assures that the predicted length of scour from our study gives the minimum floor length which prevent the occurrence of scour downstream. Also it is clearly seen that the proposed (BPN) model predicts the scour length efficiently in both cases.

Fig. 13, shows the relation between the dimensionless scour depth d_s/Y_2 and the shields' parameter τ^* in the case of arbitrary length of the rigid floor.

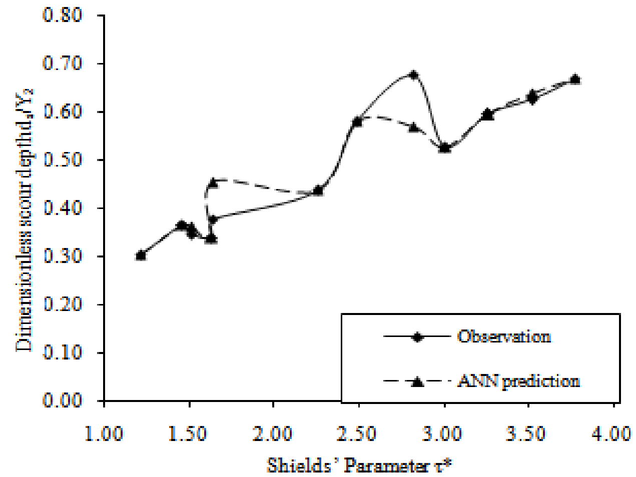

Figure 13. Comparison between the forecasting results of the BPN model and that of experimental observations for the influence of bed shear stress on the scour depth formed downstream rigid apron having length (L)

We can see that the scour hole depth depends on the bed shear stress and the values of τ^* are always greater than unity. This means that the bed shear stress due to the flow motion is greater than the critical one for moving the soil particles in the sand basin behind the arbitrary length L of the rigid floor. On the other hand, by comparing the experimental results to the predicted ones by the (BPN) model, we can find a good agreement between observed and predicted values.

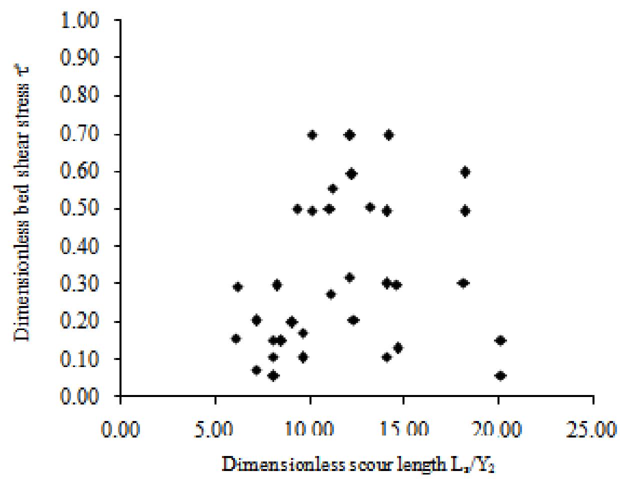

Figure 14. Variation of L_s/Y_2 with the values of τ^*

To prove that the scour length L_s represents the minimum floor length downstream the regulators, the values of shields' parameter τ^* at the end of the basin were plotted against the dimensionless scour length L_s/Y_2, as shown in Fig. 14. One can verify that the values of the shields' parameter do not exceed the unity. This means that the bed shear stress is less than the critical shear stress for the sediment particles in the sand basin. This confirms that no bed motion of the soil particles due to the flow movement over the erodible bed material found in the sand basin behind the rigid floor of length L_s. So L_s is considered the minimum length of rigid floor behind the gates of the regulators to prevent scour.

The change of the operating head of the regulators plays an important role in changing the characteristics of flow in the downstream. Fig. 15 indicates the observed and the predicted results for the variation of the dimensionless scour depth d_s/Y_2 and the dimensionless acting head H/Y_2 in case of arbitrary length L of the rigid floor. It is clearly seen that the increase of the acting head is associated with an increase of scour depth. The main cause of the scour depth increase with the acting head is the high velocity flow jet issuing from under the gates and the associated high turbulence in the downstream in the case of submerged hydraulic jump, which resulted in scour increase. Also, we can see that the proposed (BPN) model gives acceptable results in comparison to the observed ones.

4.4. Scour Predictions in Case of Asymmetrical Operation

In the field the operation of regulator may be asymmetrical under-gated regulation especially at the maintenance period, where the emergency gates are closed. For this reason it is practical to investigate the effect of the asymmetrical operation on the scour length behind the regulators. The relation between the dimensionless head difference H/Y_2 and the dimensionless scour length L_s/Y_2 or $(L+X_s)/Y_2$ is shown plotted in Fig. 16.

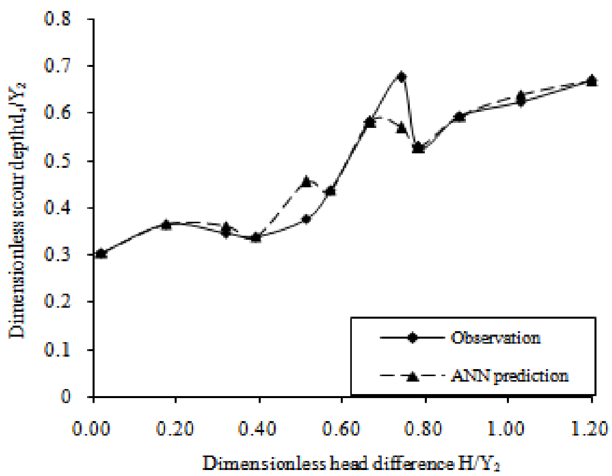

Figure 15. Comparison between the forecasting results of the BPN model and that of experimental observations for the influence of the head difference on the scour depth formed downstream rigid apron having length (L)

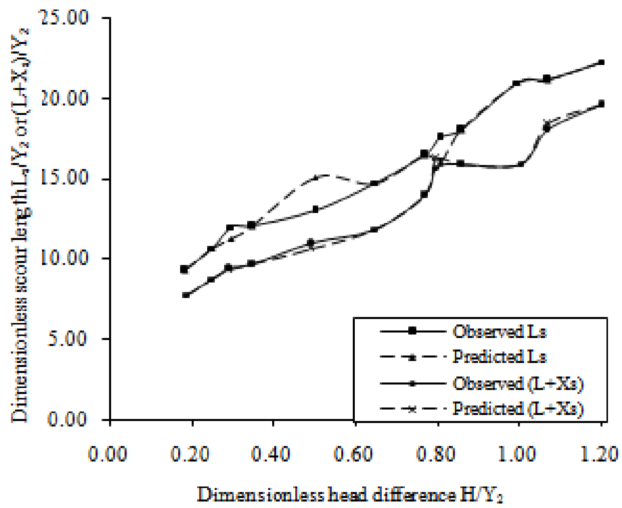

Figure 16. Comparison between the forecasting results of the BPN model and that of experimental observations for the influence of the head difference on the scour length (L_s)

Comparing the results obtained in this case to the demonstrated ones in Fig. 12, for the same value of the acting head we can see that the case of asymmetrical under-gated regulation gives scour length greater than the symmetrical case. When one or more gates are closed, the discharge of flow increases from the other opened gates which resulted in the concentration of flow to pass from them. As a result high velocity and long vortexes occurs in the downstream side in case of asymmetrical operation which resulted in increasing scour length associated with this case. Actually, asymmetrical under-gated regulation can't be overlooked because its occurrence in the field due to the need of closing one or more gates due to periodic maintenance, as we stated before in the previous sections. From the authors' point of view, we recommend that the case asymmetrical under-gated regulation should be done in the low water session and in the same time in case of low irrigation demand.

4.5. Comparison between the Results Obtained from this Study and Other Studies

Moreover the present results on L_s are depicted in Fig. 17 showing the variation of L_s/Y_2 against H/Y_2 in comparison with other researchers[39] and different regulators or barrages on the Nile River in Egypt.

Apparently, the scour length obtained from the movable bed presented herein is found to be about 3.6 times that predicted from the velocity distribution method presented by[39]. This means that the erosion depends on the amount of turbulence which is not represented by the direct measurements of the velocity distributions.

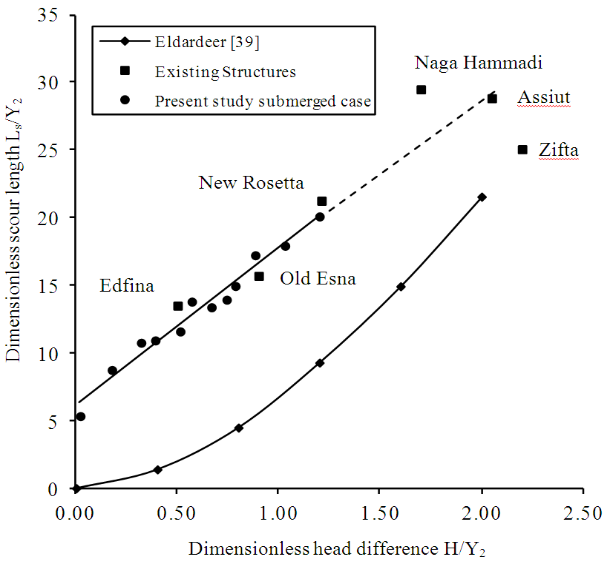

Figure 17. Comparison between L_s predicted from the present study, velocity distribution[42] and that found at existing structures[27] for symmetrical under-gated regulation

The data in Fig. 17 are quoted from[24]. The scour reaches of Assiut and old Esna barrages have been taken after the recent remodelling of these structures for the protection against the tail erosion noticed downstream of the rigid floor[24]. We can see that the present results of scour length L_s are in agreement with the existing ones for the mentioned structures.

5. Conclusions

Accurate predictions of scour depth and length downstream control structures such as regulators are essential for the stability of the structure. This article has introduced the problem of scour downstream regulators from both the experimental and theoretical point of views. Furthermore we introduced a new technique for studying the scour hole over movable bed. The study was performed under different flow scenarios, where free, submerged, symmetrical and asymmetrical conditions have been examined to try to cover all possible cases that might occur in the field. Prediction (BPN) model has been implemented to try to study the scour phenomenon using (ANNs). The following conclusions could be derived from this research:

1)- Artificial Neural Networks is very efficient tool to predict the dimensions of the scour hole, where we can avoid expensive and time consuming hydraulic model studies for various flow scenarios. Meanwhile it can predict the non-linear relationships between inputs and outputs with high correlation coefficient.

2)- The observed and the predicted values of scour depth showed the efficiency of the model to predict scour depth and length in all possible cases, where the correlation coefficient was 0.9886 for all data sets and 0.9836 for test data set for the best prediction (BPN) model.

3)- Scour hole dimensions increase in case of submerged under-gated regulations in comparison to free case.

4)- The minimum scour hole length, L_s with no scour hole allowed, is found to be longer than the length of the arbitrary length of the rigid floor, L plus the length of the scour hole X_s, formed downstream the model, $(L+X_s)$.

5)- Asymmetrical under-gated regulation is not recommended as a working regulation otherwise its effect must be taken into consideration during design process or it can be scheduled in case of low discharge periods.

Symboles

The following symbols are used in this paper

A_i : Output value of the sub-layer,
d_s: Maximum scour depth,
d_{50}: Mean particle diameter of bed material,
E: error value
f : Friction coefficient,
F_e: Froude number,
g :Acceleration of gravity,
H: Head difference between upstream and downstream water levels,
L: Arbitrary length of rigid apron behind the gates ($L<L_s$),
L_s: Minimum length of rigid apron behind the gates to prevent scour,
Q: Water flow rate,
R: Correlation coefficient,
R_e: Reynolds' number,
S: Longitudinal bed slope,
T: target output,
V_b: Velocity of flow at the end of the solid apron,
W_{ij} : Connective weight between input and hidden layers,
X_s: Length of scour hole,
Y: (BPN) output,
Y_1 : Upstream water depth,
Y_2 : Downstream water depth,
α : Momentum constant,
γ_s :Specific weight of soil particles,
γ_w :Specific weight of water,
δ : Error signal of the neuron,
ε : Parameter,
η : Learning rate of the (BPN),
μ :Dynamic viscosity,
ρ :Water density,
ρ_s :Soil particles density,
τ_b :Bed shear stress, and; τ_c :Critical shear stress.

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