Studying the Effect of Head Difference on Exit Gradients and Uplift Pressures Beneath Hydraulic Structures by Gene Expression Programming

Duaa Hadi Khashan and Waqed H Hassan

Civil Engineering Department, University of Kerbala, Kerbala, Iraq

E-mail: waaqidh@uokerbala.edu.iq

Abstract. The seeping flow under the hydraulic structure produces uplifting pressure on its floor, which affects the performance of these structures. This problem was numerically analyzed using the finite difference method in Matlab after verification with GeoStudio software. This study's main objective is to investigate the effects of head difference variation, the cutoffs’ locations, and depths on the exit gradient and uplift pressure. An empirical equation has been developed to predict the exit gradient by employing gene expression programming (GEP). More than 975 runs were executed using finite difference code with differential (H=5,10,15m), were studied over isotropic soil foundation. The results indicate that the differential head ratio (H/B) had a considerable effect on increasing the exit gradient and uplift pressure, mainly when the value of the differential head ratio (H/B =3/3) and minimum exit gradient was observed when the cutoff location ratio at the downstream is of (x1/b=1) with a maximum relative depth of (d1/b=0.6), while the minimum uplift pressure was observed when the cutoff location ratio at the upstream is of (x1/B=0) with a minimum relative depth of (d1/B=0.1). The results also indicate that the maximum exit gradient is observed when the ratio of the length of upstream cutoff to the length of downstream cutoff is (d1/d2 = 1). Based on the simulation results, the equation obtained using the Genetic expression programming (GEP) model performed better predicting to exit gradient for one cutoff with a coefficient of determination R2 equals 0.954 for training and 0.957 for testing and two cutoffs with R2 equals 0.93 for training and 0.94 for testing.

Keywords. Seepage, Finite-difference code, Piping, Uplift pressure.

1. Introduction

One of the most important problems that cause damage the hydraulic structures is seepage under the foundations, which occurs due to the difference in water level between the upstream (U/S), and downstream (D/S) sides of the structures. The water seeping underneath the hydraulic structure, endangers the structure's stability and may cause failure [1]. If a hydraulic structure is founded on a previous foundation, the dam's differential head acts on the foundation and generates under seepage. The seeping flow generates erosive forces that tend to pull soil particles with the flow. This causes the formation of irregular passages like pipes that move beneath the dam. This process is known as a piping phenomenon [2]. The leading indicator of piping difficulties conditions is the exit gradient. Piping occurs if the exit
hydraulic gradient at the downstream point approaches the critical hydraulic gradient. When the upward disturbing force on the grain is just equal to the submerged weight of the grain at the downstream point, the exit gradient is considered to be critical [3]. To prevent piping, it is necessary to reduce the seeping water's velocity to a safe value. This can be accomplished by lengthening the seepage path. One of the lengthening methods is to introduce sheet piles or cutoff walls within the dam foundation [4]. In this study, we studied the effect of differential head and other variables on the uplift pressure and exit gradient. To designed safe hydraulic structures against piping and floating due to both exit gradient and uplift pressure, we supply the hydraulic structures by cutoffs at the U.S and D.S sides of the base. In general, upstream cutoffs lower the lifting pressure and exit gradient. However, for the exit gradient, the uplift pressure is reduced at a rate higher than that for exit gradient influence. A downstream cutoff should be provided that has a significant impact on the exit gradient [5]. One of the essential reasons for the hydraulic structure's failure is seepage. It is difficult to do field experiments, so we turn to the numerical solution. We imposed a case study as a hypothesis to see the effect of some variables on exit gradient and uplift pressure. Finite difference method programming in MATLAB software was used to analyze the hypothesis case study shown in Figure 1.

This research aims to investigate the effect of the variation of head difference on the exit gradient and the uplift pressure that affects the performance of the dam and predict an empirical equation for the exit gradient by employing gene expression programming (GEP). [6, 7] studied the effect of upstream or downstream cutoffs either on the differences of exit gradient at D.S of the structure or on the uplift pressure. The results were usually provided in the form of dimensionless curves that can help in the design process. Reference [4] had used the finite element model to achieve a head distribution under the structure with angled cutoff for various soil properties and flow conditions. Reference [8] had compared the efficiency of a cutoff wall on some design parameters in an assumed diversion dam cross-section. For this purpose, different placements of the cutoff wall with various inclination angles were used in the dam foundation. The researchers state that the minimum uplift pressure occurs when the cut-off wall is in the dam's heel (upstream). With fixing the longitudinal cutoff wall placement, the cutoff wall's inclination concerning the vertical position reduces uplift pressure. In other words, the inclination of the cutoff wall upstream of the dam has a very high effect on reducing the uplift pressure. Reference [2] had presented a numerical analysis of the impact of the angled cutoff on the distribution of the hydraulic uplift pressure and the exit gradient due to hydraulic head difference. They also graphically determined the best cutoff inclination angle and its position using ANSYS11.0 for just

Figure 1. General case study and boundary conditions.
three selection locations (U.S, D.S, and midstream). Reference [9] focused on a numerical method to investigate the performance of the cutoff walls’ system against uplift pressure and piping phenomenon.

2. Material and Methodology

2.1. Finite difference Seepage modeling

The problem of seepage under the concrete dam is performed in MATLAB programming (finite difference code). The seepage equation in porous media for the three-dimensional case can be illustrated as [10]:

\[ k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} + k_z \frac{\partial^2 h}{\partial z^2} + Q + c \frac{\partial h}{\partial t} = 0 \]  

(1)

Where; \( k_x, k_y \) = hydraulic conductivity in x, y-direction, respectively. \( (L/T) \), \( Q \) = specified inflow or outflow\((L^3/T)\), and \( h \) = total head\((L)\), Equation (1) is derived with the below assumptions:

- Darcy’s law is valid throughout the seepage domain.
- The soil is saturated.
- Both soil and water are incompressible.

With these assumptions of 2D steady-state flow and \( Q \) equal to zero, the following equation is obtained:

\[ k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} = 0 \]  

(2)

This code resolves the problem and finds uplift force under the dam, head at the third floor’s dam, and exit gradient directly after entering the input data. This study concerns a dam with a partial cut-off along the floor and different locations with different depths of cutoff resting on isotropic soil on the magnitude and distribution of the exit gradient. The principle of the Finite Difference Method (FDM) is to substitute the partial derivatives of the dependent variable with a partial differential formula (PDE) with \( O(h^n) \) errors utilizing finite-difference estimations. This process converts the zone into a grid of nodes in which the predictor variables are estimated (where PDE determines the independent variables). The finite difference method is used to solve elliptic PDEs. A linear equation system was developed and solved for calculating heads at nodes using several common iterative techniques like successive over-relaxation (SOR), Jacobi, Gauss-Seidel, and combine gradient methods [11]. In this study, the approximate solution is found by the MATLAB program. The principle of flow cross a porous layer is based on Laplace’s equation of continuity, which defines the state of steady flow in the soil part for a specified place. To obtain the formula of approximation of finite difference for Laplace’s equation in x, y-direction, respectively, which are illustrated in Figure (2).

\[ \frac{\partial^2 h_i}{\partial x^2} = \frac{h_{i+1,j} - 2h_{i,j} + h_{i-1,j}}{h^2} + o(h^2) \]  

(3)

\[ \frac{\partial^2 h_i}{\partial y^2} = \frac{h_{i,j+1} - 2h_{i,j} + h_{i,j-1}}{k^2} + o(h^2) \]  

(4)

Where Equation (3) and Equation (4) are the finite-difference approximating forms for the second-order error \( o(h^2) \). Inserting these equations into Equation (1) yields:

\[ (k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2})_{(i,j)} = k_x \frac{h_{i+1,j} - 2h_{i,j} + h_{i-1,j}}{h^2} + k_y \frac{h_{i,j+1} - 2h_{i,j} + h_{i,j-1}}{k^2} = 0 \]  

(5)

\( h = k_x, k_x = k_y \text{(isotropic state)} \)

By rearranging Equation (5), the following equation is obtained

\[ h_{i+1,j} + h_{i,j+1} - 4h_{i,j} + h_{i-1,j} + h_{i,j-1} = 0 \]
So,

\[ h_{i,j} = \frac{1}{4} \left[ h_{i+1,j} + h_{i,j+1} + h_{i-1,j} + h_{i,j-1} \right] \quad (6) \]

Where \( h \) is the head at any node in the domain. In general, for the 5-point sketch, the value of \( h \) at the middle point is equal to the mean of \( h \) values at four neighboring points. The flow chart of code programming in MATLAB (finite difference code) solves Laplace’s equation shown in Figure (3). Figure (2) shows the flow chart of code programming in MATLAB (finite difference code), which solves Laplace’s equation.

**Figure 2.** The finite differences grid in X and Y directions of the flow domain.

**Figure 3.** The flow chart of the finite difference code in Matlab.
2.2. Boundary condition

The boundary conditions should be defined before beginning the solution. For the steady-state of a confined flow, the boundary conditions are illustrated as follows:

- **Boundaries of the reservoirs (Constant Head).** The water level above these limits often has a known value so that the pressure on every point of these limits are also identified; therefore, the pressure at (p) on these limits would be:

\[
p = \gamma_w h_v
\]

\[
h = h_v = p/\gamma_w + \tag{7}
\]

Thus all reservoir boundaries state equipotential lines.

- **Impervious boundary (no flow).** Concerning these boundaries, water cannot pass across the surface. It has the perpendicular velocity function on the surface equal to zero \((\partial h/\partial n = 0)\). The symbol n represents the direction of the perpendicular line on the surface.

\[
v_n = k_x \frac{\partial h}{\partial x} k_x + k_y \frac{\partial h}{\partial y} k_y = 0
\]

\[
\tag{9}
\]

where \((l_x \text{ and } l_y)\) represent the cosine of the direction of the perpendicular velocity function on the surface with the directions \((x \text{ and } y)\), respectively \[12\]. These boundary conditions are illustrated in Figure (1).

2.3. Statistical analysis by GEP

Statistical analysis is the relation involving dependent variables in the form of mathematical formulas and independent variables. In this paper, one modeling technique was used to achieve the best estimate of the dam exit gradient. This technique is Gene expression programming (GEP). Three common statistical measures identify the best strategies for predicting the exit gradient, i.e., coefficient of determination \(R^2\), root mean square error (RMSE), and mean absolute error (MAE). In this study, five parameters (differential head, depth of cutoff1, depth of cutoff2, location of cutoff1&2 on the floor of the dam) were selected as input (independent) variables, while the exit gradient obtained from the numerical simulation by finite difference code programming in MATLAB was selected as output (dependent) variable. This work’s primary purpose is to develop an empirical formula to calculate the value of the exit gradient in isotropic soil by using GEP-based models for exit gradient prediction using data optioned from the numerical simulation.

2.3.1. GEP modeling for exit gradient at the toe of the dam. A part of the genetic algorithm (Holland, 1975) is genetic programming (or GP). GP is a way to learn the most 'fit' computer programs by artificial evolution \[13\]. The mathematical functions like \((\sqrt{x}, \tan x, \sin x, x^2)\) with mathematical operations \((+, -, /, \times)\) and logical functions are used in GEP. The main purpose of GEP is to construct a mathematical function, which can be customized to a collection of the input data of the GEP model. The powerful software package named GeneXproTools 5.0 is used to develop GEP-based models for exit gradient prediction. This program gives a compact and explicit mathematical expression for the exit gradient model. The problem that can be resolved by gene expression programming is a symbolic regression (function finding), where an expression is identified appropriately describes the dependent variable. Initially, the available datasets (total of 978) of exit gradient at the toe of the dam are obtained from numerical simulation of exit gradient at different cases, the following parameters in the equation of exit gradient \(\frac{X_2}{B}, \frac{X_1}{B}, \frac{d_1}{B}, \frac{d_2}{B}, \frac{H}{B}\) are assigned to columns as independent input variable while the exit gradient \(\frac{gH}{B}\) is used as dependent output variable then a model of output variable \(\frac{gH}{B}\) is developed by using GEP. These datasets are (198) for one cutoff and (780) for two cutoffs are obtained from numerical
simulation of exit gradient under different cases. These datasets were divided into training data and testing data.

- For one cutoff, the training data consists of 158 observations (about 80%); this training data set was randomly chosen and used to build the GEP model. The validation data consisting of 40 observations (about 20%) would be used to test or verify the GEP model.
- For two cutoffs, the training data consists of 624 observations (about 80%). The validation data are consisting of 156 observations (about 20%). Various parameters for the model construction were determined after data division, illustrated in Table (1).

| Parameters                             | Values                  |
|----------------------------------------|-------------------------|
| Population size                        | 30                      |
| Mathematical operators                 | *, /, -, +, power       |
| Independent var. (x1/B, x2/B, d1/B, d2/B, H/B) | (x1/B, x2/B, d1/B, d2/B, H/B) |
| Random numerical constant (RNC)        | 5                       |
| RNC sort                               | Float point             |
| RNC scope                              | (-10, 10)               |
| Head length                            | 8                       |
| NO. of genes                           | 3                       |
| Linking                                | +                       |
| Fitness function                       | RMSE                    |
| Genetic operators strategy             | Optimal Evolution       |

3. Results and discussion

3.1. Verification of the finite difference code
Verification of the finite difference code in MATLAB 7.11.0 (R2010b) was carried out by comparing the total water head at a specific position (such as at 1/3 from the dam’s floor) and the exit gradient value obtained by the computer program Geo Studio 2018R2 SEEP/W with that obtained by the (finite difference code) to establish confidence. We use the following input variables as an example to state the verification because these variables are within the hypothesis case study, the flow under a concrete dam with one cutoff (H=10m, D=30m, B=15m, x1/b = 0 to 1, d1/B=0.2) is illustrated as in Figure 4 and 5.

![Figure 4. Scattered plot for total water head in GeoStudio versus measured in code.](image)
The comparison between the finite difference code and Geostudio seep/w shows there is a good agreement between the code and Geostudio program.

![Figure 5. Scattered plot for exit gradient in GeoStudio versus measured in code.](image)

3.2. Effect of the independent parameters on exit gradient & uplift pressure

Nine hundred eighty-one (981) runs were carried out by the numerical model (finite difference code in MATLAB) using the input variables for the case study to identify the effect of various depths and locations for cutoffs on the exit gradient and uplift pressure: differential head $(H) = 5, 10, 15 m$, floor-length $(B) = 15 m$, depth of impervious layer $(D) = 30$, and isotropic soil $(k_x/k_y = 1)$. Six various depths ratio $(d/B = 0.1:0.6)$, for each depth ratio, various cutoff locations, $(b/B = 0:1)$ were used.

3.2.1. Effect of cutoff’s location ratio on exit gradient & uplift pressure. Figures (6 and 7) were presented for $(d/B = 0.3)$ to investigate the exit gradient and uplift pressure with one cutoff. Each of these figures shows three curves for $(H/B = 1/3, 2/3, 3/3)$. These figures indicate that the value of $H/B$ had a considerable effect on increasing the exit gradient and uplift pressure, especially when the value of the differential head $(H/B = 3/3)$. The cutoff’s location on the floor directly affects the exit gradient and the uplift pressure. Using the cutoff in upstream is very effective in reducing the uplift pressure, while in downstream, it is very effective in reducing the hydraulic gradient in the exit, as shown in the figures 6 and 7.

![Figure 6. Exit gradient versus cutoff1 location ratio (d1/B=0.3).](image)

![Figure 7. Uplift force versus cutoff1 location ratio (d1/B=0.3).](image)
3.2.2. Effect of cutoff’s depth ratio on exit gradient & uplift pressure. In order to investigate the exit gradient and the uplift pressure with one cutoff, figures (8, 9, 10, 11, 12, and 13) were presented for (H/B = 1/3, 2/3, and 3/3) respectively. Each of these figures shows six curves for (d1/B = 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6). These figures indicate that the value of H/B had a considerable effect on increasing the exit gradient and uplift pressure, especially when the value of the differential head (H/B = 3/3). With increasing cutoff’s depth, the exit gradient decreases while the uplift pressure increases. Figure (8) indicates that the minimum exit gradient occurs when (d1/B = 0.6), while Figure (11) indicates that minimum uplift force occurs at (d1/B = 0.1). Accordingly, it was found that the exit gradient decreases when the cutoff’s location ratio and the cutoff’s depth ratio increase, while the uplift pressure increases with increasing the cutoff’s location ratio and the cutoff’s depth ratio.

**Figure 8.** Exit gradient versus cutoff location ratio at different values of cutoff depths d2/B=0, x2/B=0, H/B=1/3.

**Figure 9.** Exit gradient versus cutoff location ratio at different values of cutoff depths d2/B=0, x2/B=0, H/B=2/3.

**Figure 10.** Exit gradient versus cutoff location ratio at different values of cutoff depths d2/B=0, x2/B=0, H/B=3/3.

**Figure 11.** Uplift force versus cutoff location ratio at different values of cutoff depths for d2/B=0, x2/B=0, H/B=1/3.
3.2.3. Effect of two cutoffs on exit gradient. In order to investigate the exit gradient with a fixed value of the depth of cutoff1 (d1/B=0.1, x1/B=0) and different values of the depth of cutoff2, as shown in Figure 14 to 16. This figure indicates that the maximum exit gradient occurs when (d2/B=0.1) and a considerable reduction results with the increase of (d2/B) value.

Figure 12. Uplift force versus cutoff1 location ratio at different values of cut off depths for d2/B=0, x2/B=0, H/B=2/3.

Figure 13. Uplift force versus cutoff1 location ratio at different values of cut off depths for d2/B=0, x2/B=0, H/B=3/3.

Figure 14. Exit gradient versus cutoff2 location ratio at different values of cut off depths d1/B=0.1, x1/B=0, H/B=1/3.

Figure 15. Exit gradient versus cutoff2 location ratio at different values of cut off depths d1/B=0.1, x1/B=0, H/B=2/3.
3.2.4. Effect of \((d_1/d_2)\) ratio on exit gradient. The results indicate that the maximum exit gradient occurs when the length of the upstream cutoff to the length of downstream cutoff is equal to one \((d_1/d_2 = 1)\). This maximum value of the exit gradient will decrease as the ratio of \((d_1/d_2)\) decreased (increasing the cutoff depth in downstream because this ratio will significantly affect the value of the exit gradient, as shown in Figure (17).

3.2.5. Effect of differential head ratio \( (H/B)\) ratio on exit gradient & uplift pressure. In order to investigate the effect of differential head ratio \( (H/B)\) ratio on the exit gradient and the uplift pressure. Each of these figures shows above for \( (H/B = 1/3, 2/3, \text{ and 3/3})\). These figures indicate that the value of \(H/B\) had a considerable effect on increasing the exit gradient and uplift pressure, especially when the value of the differential head \((H/B = 3/3)\).
3.3. GEP Predicting model

The available datasets (total of 978) of exit gradient at the toe of the dam, (198) for one cutoff, and (781) for two cutoffs are obtained from numerical simulation of exit gradient under different cases. These datasets were divided into two groups, the first one represents one cutoff and the second one represents the two cutoffs.

*One cutoff: The training data consists of 158 observations (about 80% of the datasets); this training data set was randomly chosen and used to build this model. The validation data consisting of 40 observations (about 20% of the dataset) was used to test or validate the GEP model. The equation of the exit gradient ($g^*H/B$) is a function of the expression tree (ET) that is indicated in Figure (18) and state in Eq. (13).

$$
\frac{g^*H}{B} = ET_1 + ET_2 + ET_3
$$

**Gene1:**

Sub ET1=$[d_4 - d_3]$

**Gene2:**

Sub ET2=$[((d_4 d_4) - d_4) * d_3] + [d_4 * (d_4 + d_1)]$

**Gene3:**

Sub ET3=$[(d_2 + d_2) * d_3 e_3] - [(d_2 * (d_4 * d_2))]$

So, the exit gradient $\frac{g^*H}{B}$ formula is:

$$
\frac{g^*H}{B} = [d_4 - d_3] + [(d_4 d_4) - d_4) * d_3] + [d_4 * (d_4 + d_1)] + [(2 * d_2) * d_3 e_3] - (d_4 * d_2^2)]
$$

![Expression trees (ET) of the GEP formulation for exit gradient.](image)
The definitions of the parameters used in Equations 11, 12, 13, and 14 are represented in Table 2. The training and testing results of the GEP model are presented in Figures 19 to 22, which illustrated the curve fitting and scattered plots of measured and predicted data. The Statistical indexes results of GEP model shown in Table 3.

**Table 2. Definition of parameters in (ET).**

| No. | Error Measure | Training data | Testing data |
|-----|---------------|---------------|--------------|
| 1   | $R^2$         | 0.953         | 0.957        |
| 2   | RMSE          | 0.118         | 0.125        |
| 3   | MAE           | 0.089         | 0.095        |
| 4   | Correlation factor | 0.976       | 0.978       |

**Table 3. Statistical indexes results of GEP model.**

| Parameters | Definition |
|------------|------------|
| $d_1$      | $d_2$      |
| $d_2$      | $\beta x_1$ |
| $d_3$      | $\frac{d_1}{\beta}$ |
| $d_4$      | $\frac{\beta}{\bar{H}}$ |
| $c_4$ (gene 3) | 4.454 |

**Figure 19.** Curve fitting between predicted (yellow color) and measured (green color) exit gradient (Training data).
Figure 20. Scattered plot of measured $\frac{lg+H}{B}$ versus predicted $\frac{lg+H}{B}$ (Training data).

Figure 21. Curve fitting between predicted (yellow color) and measured (green color) exit gradient (Testing data).

Figure 22. Scattered plot of measured $\frac{lg+H}{B}$ versus predicted $\frac{lg+H}{B}$ (Testing data).
*two cutoffs*: The training data consists of 624 observations (about 85% of the dataset); this training data set was randomly chosen and used to build this model. The validation data consisting of 156 observations (about 15% of the dataset) was used to test or validate the GEP model.

The equation of the exit gradient \( \frac{g^* H}{B} \) is a function of the expression tree (ET) that is indicated in Figure (23) and stated in Equation (13).

\[
\frac{g^* H}{B} = ET1 + ET2 + ET3
\]  

**Gene1:**

\[
\text{SubET1} = d_4 \times \left[ (d_4 \times d_0) - (d_4 - d_3) \right] 
\]  

**Gene2:**

\[
\text{Sub ET2} = \left[ (d_2 \times d_4) \times (d_0 \times c_0) \right] \times \left( d_0 \times \frac{c_2}{c_3} \right) 
\]  

**Gene3:**

\[
\text{Sub ET3} = (d_2 \times d_0) 
\]  

\[
\frac{g^* H}{B} = d_4 \times \left[ (d_4 \times d_0) - (d_4 - d_3) \right] + \left[ (d_2 \times d_4) \times (d_0 \times c_0) \right] \times \left( d_0 \times \frac{c_2}{c_3} \right) + (d_2 \times d_0) 
\]  

**Figure 23.** Expression trees (ET) of the GEP formulation for exit gradient.
The definitions of the parameters used in Equations 16, 17, 18, and 19 are represented in Table 4. The training and testing results of the GEP model are presented in Figures 24 to 27, which illustrated the curve fitting and scattered plots of measured and predicted data. Also, the statistical results of the GEP model shown in Table 5.

### Table 4. Definition of parameters in (ET).

| Parameters | Definition |
|------------|------------|
| $d_0$      | $xZ$       |
| $d_2$      | $\frac{B}{d2}$       |
| $d_3$      | $\frac{B}{d1}$       |
| $d_4$      | $\frac{B}{H}$       |
| $c_0$ (gene 2) | 8.928 |
| $c_2$ (gene 2) | -2.720 |
| $c_3$ (gene 2) | 9.020 |

### Table 5. Statistical results of the GEP model.

| No | Error measure | Training data | Testing data |
|----|---------------|---------------|--------------|
| 1  | $R^2$         | 0.932         | 0.943        |
| 2  | RMSE          | 0.120         | 0.104        |
| 3  | MAE           | 0.082         | 0.071        |
| 4  | Correlation factor | 0.965 | 0.971 |

**Figure 24.** Curve fitting between predicted (yellow color) and measured (green color) exit gradient (Training data).
Figure 25. Scattered plot of measured $\frac{i_{g+H}}{B}$ versus predicted $\frac{i_{g+H}}{B}$ (Training data).

Figure 26. Curve fitting between predicted (yellow color) and measured (green color) exit gradient (Testing data).

Figure 27. Scattered plot of measured $\frac{i_{g+H}}{B}$ versus predicted $\frac{i_{g+H}}{B}$ (Training data).
These results show that GEP gave a high value of $R^2$ for the testing data for one cutoff and two cutoffs. Thus, this refers to a perfect estimation of the exit gradient because of a minimal discrepancy between measured and predicted exit gradient and a low value of RMSE and MAE, implying a good performance of the applied method.

4. Conclusion
The conclusions of this study are:

1. Using the cutoff at the upstream effectively reduces the uplift pressure, while the cutoff at the downstream is very effective in reducing the exit gradient. The exit gradient decreases with increasing the cutoffs’ location ratio and the depth ratio, while the uplift pressure increases with increasing these ratios.

2. At $H/B=2/3$, the results indicated that the minimum exit gradient was achieved 0.163 at $d/b$ equal to 0.5 with F.O.S equals 6.13 when the cutoff location is downstream, but the uplift force was reached the maximum (474). For two cutoff depth values studied, the minimum exit gradient is achieved 0.368 with F.O.S equals to 3.34 for minimum uplift force 735 when the cutoff1 location in upstream and the cutoff2 at downstream with a $(d/b)$ equal to or more than 0.3, so the factor of safety against piping phenomena in the safe side.

3. The results indicate that the differential head $(H/B)$ value had a considerable effect on increasing the exit gradient and uplift pressure, especially when the differential head value $(H/B = 3/3)$.

4. The minimum exit gradient was observed when the cutoff location ratio at the downstream is of $(x_1/b=1)$ with a maximum relative depth of $(d_1/b=0.6)$, while the minimum uplift pressure was observed when the cutoff location ratio at the upstream is of $(x_1/B=0)$ with a minimum relative depth of $(d/B=0.1)$.

5. The results indicate that the maximum exit gradient is observed when the length of the upstream cutoff's length to the length of downstream cutoff is $(d_1/d_2 = 1)$. This maximum value of the exit gradient decreases as the ratio of $(d_1/d_2)$ decreases and is significantly reduced as the $(d_1/d_2)$ ratio decreased.

6. The GEP model gave a high value of $R^2$ for computing the exit gradient and a low value of RMSE and MAE, implying the model's good performance.

7. The equations of exit gradient predicted by GEP are a good alternative to calculate the exit gradient directly after entering the required variables.

8. We can also use the dimensionless figure in design any hydraulic structure with input variables different from the studied variables.

5. References
[1] Al-Musawi W H, A H K Shukur and A A Al-Delewy 2006 Optimum Design of Control Devices for Safe Seepage Under Hydraulic Structures (Journal of Engineering and Sustainable Development) vol 10 no 1 pp 66-87
[2] Al-Saadi S I K, H T N Al-Damarchi and H C Al-Zrejawi 2011 Optimum Location and Angle of Inclination of Cut-Off to Control Exit Gradient and Uplift Pressure Head Under Hydraulic Structures (Jordan Journal of Civil Engineering) vol 159 pp 1-12
[3] Hassan W H 2019 Application of a Genetic Algorithm for the Optimization of a Location and Inclination Angle of a Cut-Off Wall for Anisotropic Foundations Under Hydraulic Structures (Geotechnical and Geological Engineering) vol 37 pp 883-895
[4] Alsenousi K F and H G Mohamed 2008 Effects of Inclined Cutoffs and Soil Foundation Characteristics on Seepage Beneath Hydraulic Structures (Twelfth International Water Technology Conference), Alexandria, Egypt
[5] Al-Suhaili R H and R A Karim 2014 Optimal Dimensions of Small Hydraulic Structure Cutoffs using Coupled Genetic Algorithm and ANN Model (Journal of Engineering) vol 20 no 2 pp 1-19
[6] Griffiths D and G A Fenton 1993 Seepage Beneath Water Retaining Structures Founded on Spatially Random Soil (Géotechnique) vol 43 no 4 pp 577-587
[7] Rafa H. Al-Suhaili 2009 Analytical Solution for Exit Gradient Variation Downstream of Inclined Sheet Pile (The 6th Engineering Conference of Engineering College, College of Engineering, University of Baghdad, Iraq)
[8] Mansuri B, F Salmasi and B Oghati 2014 Effect of Location and Angle of Cutoff Wall on Uplift Pressure in Diversion Dam (Geotechnical and Geological Engineering) vol 32 no 5 pp 1165-1173
[9] A Moharrami, G Moradi, M H Bonab, J Katebi and G Moharrami 2015 Performance of Cutoff Walls Under Hydraulic Structures Against Uplift Pressure and Piping Phenomenon (Geotechnical and Geological Engineering) vol 33 no 1 pp 95-103
[10] M C Manna, A K Bhattacharya, S Choudhury and S C Maji 2003 Groundwater Flow Beneath a Sheetpile Analyzed Using Six-Noded Triangular Finite Elements (Department of Applied Mechanics, Bengal Engineering College, Deemed University) vol 84 pp 121-129
[11] Al-Rob M F A A 2016 Finite Difference and Finite Element Methods for Solving Elliptic Partial Differential Equations (DuraSpace)
[12] Hassan W H 2017 Application of a Genetic Algorithm for the Optimization of a Cutoff Wall Under Hydraulic Structures (Journal of Applied Water Engineering and Research) vol 5 no 1 pp 22-30
[13] A. Johari, G. Habibagahi and A. Ghahramani 2006 Prediction of Soil–Water Characteristic Curve Using Genetic Programming (Journal of Geotechnical and Geoenvironmental Engineering) vol 132 no 5 pp 661-665