Research Article

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Investigation of effect lengths and angles of the control devices below the hydraulic structure

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Abstract: This study investigated the effect of reducing seepage under a hydraulic structure. This article aims to find positional equations for the control devices that reduce the seepage under the hydraulic structure. Using lengths and angles of sheet-piles under the hydraulic structure where the sheet-pile was placed up- and downstream, respectively, upon the hydraulic structure with anisotropy soil hypothetically affects both uplift pressure and seepage values. The experiments were conducted in two cases: in the first case, a couple of sheet-piles were oriented to the upstream passage; while in the second case, they were oriented to the downstream. Then, the second case was compared with three sheet-piles placed upstream, downstream, and intermediate to the passage. For each experiment (at the hydraulic toe position), the major affecting parameters such as the uplift pressure, gradient exit, and outlet flow rate were found. A correlation equation to correlate the exit gradient and discharge parameters was developed.

Keywords: discharge, uplift pressure, SEEP/W, exit gradient, seepage, non-homogenous soil

Nomenclature

\[ B \] distance between sheet piles (L)
\[ d_1 \] depth of the first sheet-pile (L)
\[ d_2 \] depth of the second sheet-pile (L)
\[ d_3 \] depth of the intermediate sheet pile (L)
\[ H \] upstream head (L)
\[ I \] exit gradient (L/L)
\[ k_x \] hydraulic conductivity of soil in the x-direction (L/T)
\[ k_y \] hydraulic conductivity of soil in the y-direction (L/T)
\[ p \] uplift pressure head (L)
\[ q \] discharge (L²/T/L)
\[ \alpha \] angle of the last sheet-pile
\[ \beta \] angle of the intermediate sheet-pile
\[ \theta \] angle of the first sheet-pile

1 Introduction

From the earth’s formation, water forces played a vital role in the morphology of earth terrains. The water forces are responsible for all constructions and earth compositions. It also vouch for the earth’s stability and properties. Meanwhile, seepage is permanently available and represents a chronic issue for earth structures and threatened human societies while it seeps through pores.

Even today, many engineers have tried to study the nature of the underground water flow. Various theories and investigations have been put forward to predict the phenomenon of many experiments, and investigations are still underway to make the engineering structures use this precipitated hydropower for the benefit of mankind. Various methods are successfully employed to analyze the seepage problems. Sheet-piles, grout curtains, impervious cutoff trenches, and impervious are widely used to control seepage.

The stability of earth structures and natural deposits depends on the soil’s static properties and the forces produced by water as it seeps through the pores. As an aid to engineering judgment in the design of earth structures or the stabilization of earth deposits, the engineer should be talented in estimating, by analyzing, the magnitude of seepage forces and pressures and the quantities of water.

The optimal exploitation of water resources is not yet achieved. Hence, an innovative approach should be followed...
for that purpose. The previous aim could be guaranteed by embracing a hydraulic stan engineering solution to overcome such issues. The hydraulic structure has many applications in modern irrigation and water control systems. It is vital in water distribution channels by serving water level adjusters; dams serve as flow rate regulators and weirs.

Many researchers put effort in this field to reveal the importance of hydraulic structures. A study that employed a couple of filters positioned on a flat floor was conducted by Farouk and Smith [1]. A least-squares finite element modeling (FEM) was adopted as a tool to study the non-linear permeability seepage by Mohsen [2]. A safe seepage was examined and studied by a control device to get oral control of the hydraulic structure by Al-Deleyw et al. [3]. The study focused on seepage under the hydraulic structure using a filter and blanket. Arslan and Mohammad [4] scrutinized an inclined sheet-pile when the arrangement was placed under a hydraulic structure with a piezometric head. A finite volume (FEM) was employed in the seepage analysis through and under the hydraulic structure by Evans [5]. The current study aims to clarify how exit gradient and uplift pressure (placed downstream) affect the presence of heterogeneous foundations.

The study is also concerned with both the obstacle's position and inclination at the beginning, and end of the hydraulic structure. In addition, the impermeable body influences both the exit gradient and upstream pressure. Experimentations and FEM simulations were conducted under lab conditions by Khalili Shayan and Amiri-Tokaldany [6]. These tests were carried out on a diversion hydraulic to get a comprehensive understanding of the major parameters such as uplift force, exit gradient, and slope. The reported outcomes were gathered in a case of a separation wall arranged downstream. FORTRAN 90 program was built by Moharrami et al. [7] to predict the main affecting parameters of the cutoff wall, such as both inclination angles on seepage. A complete outcome set regarding drain seepage behind the oblique cutoff walls was obtained. In addition, the exit gradient and pressure head (at a nodal point) were obtained. The effects of both obstacle and seep holes on the exit gradient and uplift pressure mitigation were numerically studied by El Molla [8]. The study proposed a method that helps reduce costs by shunting dams. The flow seepage underneath the dam and the employment of an inclined cutoff were scrutinized analytically by Rezk and Elela [9]. Olsen et al. [10] scrutinized the downstream bottom of the hydraulics to find both the hydraulic gradient and pressure at specific spots, especially the key point. This study proposed an equation for the outcome predictions. In addition, the influence probability of seepage underneath the hydraulic structures by various parameters was studied, especially the sheet-pile substrate formation, the use, and the exit gradient.

In a small hydraulic structure, the foundations are given more importance in the analysis than other parts of the structure since the failure of the foundations means destroying the whole structure. The main problem causing damage to hydraulic structures is seepage under the foundation, the difference in the water level between the source (U/S), or (D/S), and the sides of the structures. The seepage water starts from the bottom of the hydraulic chassis base from the U/S side and tries to exit at the D/S end of the impermeable floor. If the exit gradient is greater than the critical value of the foundation, a phenomenon called piping may occur due to continuous washing and removal of subsoil grains [4,11,12].

Moreover, the uplifting force due to waterproofing under the structure exerts high pressure on the structure's floor. If the weight of the floor does not balance this pressure, the structure may fail by rupturing part of the floor. Piping and lifting problems are virtually addressed through various seepage control methods to ensure the integrity of the structure in question while saving potential water leaks. Previous numerical and experimental studies have studied various measures to control leakage under hydraulic structures, such as blankets [10], cutoff walls [13,14], plate piles [15], and filters [16,17]. Also, a method of initial representative active volume was used to improve the computation of exit gradients in seepage assessments supporting this method with the use of FEM [18–21].

The basic aim of these structures is to control the flow discharge and water levels. Because of all the aforementioned facts, this research work is designed to model seepage analysis of a hydraulic structure using an SEEP/W program. Given all the aforementioned facts, this work has been designed to model seepage analysis of the hydraulic structure using the SEEP/W program.

2 Procedure

The experimentations were conducted in two situations or cases where a bunch of pile sheets was raced by the SEEP/W test model. An arrangement of piles having double pile sheets was placed upstream and downstream, respectively. On the other hand, an arrangement of a pile having three pile sheets was employed and distributed upstream, midstream, and downstream, respectively, for the second case. Each of the two cases had different values for each variable. The upstream sheet-pile angles were \( \theta = 90, 20, 30, \) and 40°.
For the downstream sheet-pile also, the angles were $\alpha = 20, 30, 0$, and $90^\circ$, while the intermediate sheet-pile angle values were $\beta = 20, 30, 40$, and $90^\circ$. The ability ratios were $K_x/K_y = 0.3, 0.8, 2.5,$ and $7$. Finally, the depth of the second sheet-pile was $d_2 = 2 \text{ m}$, and the depth of the intermediate sheet-pile was $d_3 = 3 \text{ m}$. Therefore, the number of iterations in the examinations was 64 iterations belonging to the first case and 255 iterations for the second one, respectively. The major parameters, such as discharge, uplift, and exit gradient, are determined in this investigation. Figure 1 depicts the schematic algorithm of the cases mentioned above.

3 Design variables

The major parameters having the dominant effects underneath the hydraulic structure are exit gradient, uplift, and discharge:

$$\begin{bmatrix} q \\ P \end{bmatrix} = f(\theta, \alpha, \beta, b, h, d_1, d_2, d_3, K_x/K_y).$$

To develop an empirical correlation that can predict the major parameters (uplift, discharge, and exit gradient) thoroughly at the start point of the hydraulic structure, the previous correlation would be broken down and discretized by exempting some undesired variables as follows:

$$\begin{bmatrix} q \\ P \end{bmatrix} = f(\theta, \alpha, \beta, K_x/K_y).$$

Figure 2 depicts the impacts of the hydraulic structure’s uplift, discharge, and exit gradient.

4 Results and discussion

A group of data was used in the SEEP/W program, where a comparison was made between the two cases using two and three sheet-piles, as shown in equation (2). Figure 3 shows the relationship between the angle of the last sheet-pile with the head of the lifting pressure (P) at the hydraulic toe with boundary conditions for the constant angle of the sheet-piles (\(\theta\)), constant depth, and constant permeability ratio (\(K_x/K_y\)) for all the sheet-piles.

As shown in Figure 3, when using an intermediate lamellar sheet-pile, the greatest effect on the volume of the uplift pressure head can be observed (P). It seems that it decreases gradually as \(\alpha\) increases but when \(\alpha = 90\), the uplift pressure increases. Also, it can be seen that when the first, intermediate, and last sheet-piles were used with \(\beta = 20^\circ\) or \(90^\circ\), the head of the uplift pressure decreases almost gradually (7, 4, 2, and 1.2%) with the permeability ratios \(K_x/K_y = 0.3, 0.7, 2.5,$ and $7$, respectively. But when the intermediate sheet-pile was used with \(\beta = 30^\circ\), we

Figure 1: Schematic algorithm of arrangement of cases.
noticed that the head of the uplift pressure decreased by about 6.5, 3.8, 2, and 1.1% for the permeability ratios $K_x/K_y = 0.3, 0.8, 2.5,$ and 7, respectively. When using an intermediate sheet-pile with an angle $\beta = 40^\circ$, the uplift pressure decreased by 6, 3.6, 3, and 1.5% when $K_x/K_y = 0.3, 0.8, 2.5,$ and 7, respectively. Also, we noticed when $\beta = 20^\circ$ for the intermediate sheet-pile at $K_x/K_y = 0.3, 0.8, 2.5,$ and 7, the results showed a maximum lifting pressure, while using an intermediate sheet-pile at $\beta = 20^\circ$ and $K_x/K_y = 0.3$, the lifting pressure is the minimum.

From Figure 4, we notice the relationship between the angle of the last sheet-pile and the exit gradient ($I$) at the front of the structure where the angle of the first pile ($\theta$), the depth of all files, and the permeability ratio $K_x/K_y$ remain constant. It can also be seen that increasing the angle $\alpha$ leads to an increase in the exit gradient $I$, but we notice that $I$ decrease when $\alpha = 90^\circ$. When using an intermediate sheet pile with $\beta = 20, 30, 40,$ and $90^\circ$ next to the first and last sheet-piles, we notice $K_x/K_y = 0.3$; the exit gradient $I$ decrease to approximately 5.1%, and in the case of $K_x/K_y = 0.8$, the exit gradient $I$ decreases to approximately 9.5, 8, 5.8, and 3.5%. When $\alpha = 90, 40, 30,$ and $20^\circ$ and $K_x/K_y = 2.5$, then $I$ decreases by approximately 14, 12, 8.5, and 3.5%. When $K_x/K_y = 7$, the exit gradient $I$ decreases by about 18, 12, 10.5, and 2.5%.

From the above, it is possible to find the highest and lowest values of the exit gradient $I$. We noticed that when $\alpha = 90^\circ$ with the last sheet-pile and $K_x/K_y = 7$, then the exit gradient $I$ had the highest value; whereas when $\alpha = 40^\circ$ with the last sheet-pile and $K_x/K_y = 7$, then the exit gradient $I$ had a minimum value.
Figure 5 represents the relationship between $\alpha$ of the last pile and the discharge ($q$) at the front of the structure under constant boundary conditions for the first angle $\theta$, with the depth and $K_x/K_y$ being constant for all plate piles. From this figure, we conclude that increasing $\alpha$ leads to increases in $q$, but $\alpha = 90^\circ$ then $q$ decreases. Moreover, when the intermediate sheet-pile is used along with the first and last sheet-piles at $\beta = 20, 30, 40,$ and $90^\circ$, $q$ decreases by about 5.2% at $K_x/K_y = 0.3$. In addition, for $K_x/K_y = 0.8$, the discharge decreases by about 10, 7.5, 6, and 4% when $\alpha = 90$, 20, 30, and 40°. When $\alpha = 90^\circ$ and $K_x/K_y = 2.5$, the discharge decreases by approximately 4%, but when $\alpha = 20, 30,$ and $40^\circ$ and $K_x/K_y = 7$, the discharge increases by 2.5%. Therefore, it can be seen from the above result that $q$ is maximum when $\alpha = 30^\circ$ for the last sheet-pile and $K_x/K_y = 7$, while $q$ is minimum when $\alpha = 90$ for the last sheet-pile and $K_x/K_y = 0.8$.

### 4.1 The variables and their relationship to the middle sheet-pile

From the results obtained from the SEEP/W program, the relationship among the variables $P$, $q$, and $I$ was obtained.
In the figure, the decrease in the angle $\beta$ leads to an increased uplift pressure $P$ in the front of the hydraulic structure. The uplift pressure $P$ increases by about 0.38% when $\beta$ decreases from 90 to 20° and when $\beta$ decreases from 90 to 30°; the uplift pressure increases to 0.35%, and it increases by 0.4% when $\beta$ decreases from 90 to 40°. Also, the figure shows that when $P$ decreases gradually, then soil permeability increases.

Figure 9 shows the relationship between $I$ and $\alpha$ at $\theta = 90^\circ$ and $\beta = 90^\circ$.

As shown in the figure, the exit gradient $(I)$ gradually decreases with increasing soil permeability; when permeability increases from 0.1 to 0.5, the exit gradient $(I)$ is less than 30% and decreases by about 34% when the permeability ratio increases from 0.5 to 2 and decreases by approximately 26% when the percentage of transmittance increases from 2 to 5.

Figure 10 shows the relationship between $I$ and $\theta$ of the first sheet pile. The constant conditions were the angle for the last sheet-pile and middle ($\alpha$, $\beta$) and constant depth for all sheet-piles, with the permeability used in four different ratios ($K_x/K_y$). It can be seen from the figure that $I$ decreases gradually as $\theta$ increases but when $\theta = 90^\circ$, $I$ increases. When $\theta$ decreases from 90 to 20°, the exit gradient decreases by about 2%, when $\theta$ decreases from 90 to 30°, the exit gradient decreases by about 2.4%, and when $\theta$ decreases from 90 to 40°, the exit gradient decreases by about 3.1%.

Figure 10: Relationship between $\theta$ and $I$ at $\alpha = 90^\circ$ and $\beta = 90^\circ$. 
Figure 11: The relationship between $\beta$ and the exit gradient $I$ at $\theta = 90^\circ$ and $\alpha = 90^\circ$.

Figure 11 shows the relationship between $I$ and $\beta$ of the intermediate sheet-pile. The constant boundary condition is $(\theta, \alpha)$, and the constant depth for the three sheet piles, but the permeability ratios $K_x/K_y$ differed. We also note from the figure that with the increase of $\beta$, the exit gradient decreases. We notice that the exit gradient increases by about 0.05% when $\beta$ decreases from 90 to 20°, it increases by approximately 0.047% when $\beta$ decreases from 90 to 30°, and it increases by 0.067% when $\beta$ decreases from 90 to 40°. This figure also shows a decrease in the exit gradient with increasing soil permeability.

Figure 12 shows the relationship between the discharge ($q$) at the front of the hydraulic structure and the angle at the last of the sheet pile. The boundary conditions are constant angles at the first sheet-piles $(\theta, \beta)$. The depth is constant for all three piles, and four different permeability ratios $(K_x/K_y)$ were used. It is shown when $\alpha$ increases, $q$ increases but the discharge decreases when $\alpha = 90^\circ$. When $q$ increases by 7.4%, $\alpha$ decreases from 90 to 20°, when $\alpha$ decreases from 90 to 30°, $q$ increases by 7.7%, and when $\alpha$ decreases from 90 to 40°, $q$ increases by about 5.2%. The figure also shows the decrease in the permeability ratio of the soil whenever the discharge decreases; when the permeability ratio increases from 0.1 to 0.5, the discharge increases by about 72%, when $K_x/K_y$ increases from 0.5 to 2, the discharge increases by 62%, and when $K_x/K_y$ increases from 2 to 5, the discharge increases by 42%.

Figure 13 represents the relationship between the discharge ($q$) in the front of the structure and $\theta$ of the first pile, and the two remaining angles for the third sheet-piles $(\alpha, \beta)$ and constant depth and four different permeability ratios $(K_x/K_y)$. This figure shows that the discharge decreases with an increase in $\theta$ but increases at $\theta = 90^\circ$. When $\theta$ decreases from 90 to 20°, the discharge decreases by ~2%, and when $\theta$ decreases from 90 to 30°, the discharge decreases by ~2.4%, and when $\theta$ decreases from 90 to 40°, it decreases by ~3%. The drainage decreases with the decrease in the permeability of the soil.

Figure 14 shows the relationship between the discharge ($q$) at the front of the hydraulic structure and the intermediate sheet-pile angle. The angles are constant for
the first and last sheet-piles (θ, α) and the depth is constant for the three sheet piles, whereas four different permeability ratios (Kx/Ky) were used. As seen from the figure, a decrease in β leads to an increase in the discharge. q increases by 0.05% when β decreases from 90 to 20°, it increases by about 0.046% when β decreases from 90 to 30°, and it increases by about 0.058% when β decreases from 90 to 40°.

In this article, special equations for p, I, and q will be obtained at the front of the structure. We obtain the following equations when roughly substituting the SEEP/W program results of the cases in the SPSS-19 Statistics, which is used to determine p, I, and q at the front of the structure in anisotropy soils:

$$P = \frac{1.009 \times 0.0007}{\beta^{0.00274} \times \alpha^{0.0015397} \times \left(\frac{K_x}{K_y}\right)^{0.279}},$$  \hspace{1cm} (3)

($R^2 = 0.97$) (Pearson correlation = 0.953),

$$I = \frac{0.373 \times \beta^{0.006} \theta^{0.008}}{\alpha^{0.067} \left(\frac{K_x}{K_y}\right)^{0.036}},$$  \hspace{1cm} (4)

($R^2 = 0.913$) (Pearson correlation = 0.961),

$$q = \frac{0.6791 \times 10^{-6} \times \beta^{0.009} \times \theta^{0.009} \times \left(\frac{K_x}{K_y}\right)^{0.781}}{\alpha^{0.042}},$$  \hspace{1cm} (5)

($R^2 = 0.92$) (Pearson correlation = 0.917).

Figures 15–17 show the comparison among the uplift pressure, the exit gradient, and the discharge, respectively, by using the SEEP/W program and the results obtained by equations (3)–(5) where they used the same properties and conditions, which are the geometric boundaries. The results matched well.

5 Conclusions

This article represented the simulation of p, I, and q at the front of the structure in anisotropy soil using the SEEP/W program.

We conclude the case of the use of two sheet-piles as follows:

1 – We noticed the greatest effect using the median sheet piles, where the uplift pressure decreases as the α angle value increases. Still, the uplift pressure increases when α = 90°. We obtained the greatest uplift pressure at $\beta = 20°$ and $K_x/K_y = 5$ for the middle sheet-pile, but when $\beta = 20°$ and $K_x/K_y = 0.3$ for the middle sheet-pile, we observed the least uplifting pressure.

2 – The exit gradient increases with the increase of α but it decreases when α = 90°. A minimum value of I is obtained when using the last of the pile with α = 40° and $K_x/K_y = 7$. 

Figure 15: A comparison between the uplift pressure calculated from equation (3) and the measurement using the SEEP/W program.

Figure 16: A comparison of I obtained from equation (4) with the output using the SEEP/W program.

Figure 17: A comparison of q obtained by equation (5) with the output using the SEEP/W program.
3 – The value of the discharge increases with increasing α. The largest discharge value was obtained when α = 30° and \( K_x/K_y = 7 \) for the last sheet-pile; however, we notice that when α = 90° and \( K_x/K_y = 0.8 \), we obtained the least discharge for the last sheet.

But when using three sheet piles in the second case, we noticed the following:
1 The maximum uplift pressure decreases by about 0.97% when α decreases from 90 to 20°.
2 The maximum uplift pressure decreases by about 4% when α decreases from 90 to 40°.
3 The maximum (p) increases by about 0.7% when the β value decreases from 90 to 40°.
4 The maximum (z) is as high as possible, 9.2% when α decreases from 90 to 40°. We also saw that the exit gradient gradually decreases with increasing soil permeability.
5 We noticed that when θ decreases from 90 to 40°, the highest value of the decrease in the external gradient is 4.1%.
6 The maximum degree of the exit gradient line is about 0.079% when β decreases from 90 to 40°.
7 The maximum discharge increases by 9.1% when α decreases from 90 to 30°.
8 The maximum drainage deficiency was about 4% when θ decreases from 90 to 40°.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: Most datasets generated and analyzed in this study are in this manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

References