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Performance of Lateral Cutoff Wall on Seepage Characteristics Around Hydraulic Structures

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***Abstract* -** Effect of the cutoff wall in 2D on the seepage characteristics, exit gradient, and uplift pressure has been extensively studied in previous studies; however, the impact of the lateral cutoff wall of various lengths and depths on side seepage and the overall stability of the hydraulic structures has yet to be fully understood in the 3D analysis. The main objective of this study is to investigate the effect of lateral cutoff on seepage discharge, uplift force, and the exit gradient for hydraulic structures founded on finite and infinite pervious strata. The analysis is carried out numerically by using a computer program, utilizing the finite element method (Midas GTS NX). Several configurations of the cutoff wall driven under the structure and extended laterally are analyzed including penetration depth, cutoff wall location, lateral length, and thickness of the foundation. The results of the Midas GTS NX are in good agreement with those of prior analytical and experimental studies. The numerical results confirmed that cutoff walls fixed downstream of the floor, substantially reduce the exit gradient; however, it slightly increases the uplift force acting on the structure. Seepage quantity and exit gradient do not increase any further when the soil foundation thickness to the structure length exceeds 2.18 and 2.27, respectively. An increase in the value of the uplift force is noticed with increasing the pervious soil foundation thickness for cutoff walls fixed before the mid-length of the structure. However, positioning the cutoff further downstream decreases the uplift force while increasing the pervious soil foundation thickness.

***Keywords*:** Cutoff wall, Exit gradient, Numerical modeling, Seepage discharge.

1. Introduction

Hydraulic structures with different water elevations on both ends are subjected to seepage through foundation soil. If this is not carefully examined, it may lead to the risk of failure of the whole structure and subsequently to great economic loss. So, the stability of hydraulic structures has to be insured against the effect of seepage characteristics represented in the uplift force, exit gradient, and seepage discharge. To avoid the risk of hydraulic structure failure, the structure must be designed properly to provide greater resistance against uplift forces to prevent risks due to water pressure since rehabilitation and maintenance of foundation cannot be carried out easily in the future also when water flows through the pervious foundation of any hydraulic structure with a high exit gradient, the structure may fail because of piping. These design problems are not well understood in the case of 3D analysis. Researchers usually took a traditional approach in studying seepage flow under hydraulic structures without any regard to the flow moving through the surrounding banks of the canal.

Different methods have been developed to estimate the seepage discharge like approximate [1, 2], analytical [3-6], experimental [7, 8], empirical [9, 10], and numerical methods.

One of the most numerical well-known programs in seepage analysis is Geo-Studio software Seep/w (GEO-SLOPE). [11] analyzed flow characteristics of an impervious dam with a cutoff wall on a layered soil and the results were reduced to simple charts allowing any designer to obtain solutions. [12] studied seepage through porous media underneath a hydraulic structure with vertical cutoff walls. He found that the downstream cutoff is more effective than the upstream one in reducing the exit gradient. [13] and [14] found that increasing the length of the upstream cutoff wall decreases the total uplift pressure and decreases the maximum exit gradient. [16] studied the effect of using upstream and downstream sheet piles, in a double soil layer with the first layer having a coefficient of permeability more than the second one, on the seepage discharge, uplift pressure, and exit gradient and he found that the seepage discharge, uplift force, and exit gradient increase with increasing the depth of the first soil layer. [17] studied the effect of two sheet piles on seepage rate and exit gradient under a concrete dam and confirmed that the distance between sheet piles, inclination angle, and length of downstream pile can be considered important factors affecting the exit gradient over other variables. For the seepage rate, the most prominent factors affecting it after coefficient of permeability and head difference are the spacing between sheet piles, as the seepage rate and exit gradient are reduced as this distance is increased. [18] studied the effect of mutual interference of sheet piles on seepage phenomenon by using finite elements program, ANSYS. He found that the use of the two sheet piles, one on the upstream end and the other on the downstream end, reduced the uplift pressures by 8.36% at upstream, while in the downstream it increased it by 11.66% compared to the case of using no sheet piles at all. Meanwhile, the total seepage flow rate and the exit gradient are reduced by 66.8, and 28.3%, respectively.

As can be seen, two-dimensional analysis is commonly used to calculate seepage in hydraulic structures. However, it is not always appropriate to make the solution simpler by reducing the problem to a two-dimensional problem. In some cases, a three-dimensional study is required. A few publications studied the seepage characteristics in a 3D analysis like [20] in which he made a comparison between electric analog results [21] and finite element results using SWICHA program to study the effect of lateral cutoff and lateral relief filter on seepage characteristics. He concluded that the exit gradient using 3D analysis is more than that obtained by 2D analysis. Also, [22] investigated the influence of various sheet pile configurations on the seepage characteristics and it was observed that extending the sheet pile laterally through the banks of the canal has no appreciable influence on either uplift force acting on the structure or the exit gradient at the end toe of the floor.

According to the authors, 3D examination of seepage beneath hydraulic structures necessitates additional studies and research. The influence of lateral cutoff walls, their depths, lateral extensions, and positions on seepage characteristics (flow rates, exit gradients at the structure's edges and centerline, uplift pressures) is still being studied, as is the effect of previous foundation thickness.

2. Verification of the Model

To verify the use of the computer program in the present study, a 2D verification is done by comparing the results of Midas GTS NX program with analytical solutions found in literature while a 3D verification is also done by comparing its results with experimental ones. The correlation coefficient, R^2, is used to quantify the goodness of the results.

2.1. 2D Verification

[3] obtained the distribution of uplift pressures acting on the base of a structure without the use of sheet piles. Also, [6] gave the seepage discharge for symmetrically placed piles as a function of the depth of embedment. For exit gradient, [24] obtained the values of exit gradient for structures with sheet piles on an impervious foundation of finite depth. The model results indicate a good fit with these analytical results in estimating the seepage discharge, uplift force, and exit gradient with an R-squared value equal 0.99 for each.

2.2. 3D Verification

[8] experimentally studied the problem of seepage around a head or tail hydraulic structure founded on a finite pervious stratum by a three-dimensional electric analog model. He studied the effect of the structure position and the thickness of the pervious stratum on seepage characteristics. Figure (1) shows a schematic sketch of the physical problem used in verification. The 3D electric analog model has relative dimensions, E/L=2, M/L=1.50, t/L= 0.085, and B/L=1.60 where E is the structure width, L is the structure length in the longitudinal direction, M is the pervious foundation thickness, t is the structure thickness embedded in the foundation, B is the channel width and L_c is the structure position from the end channel II.

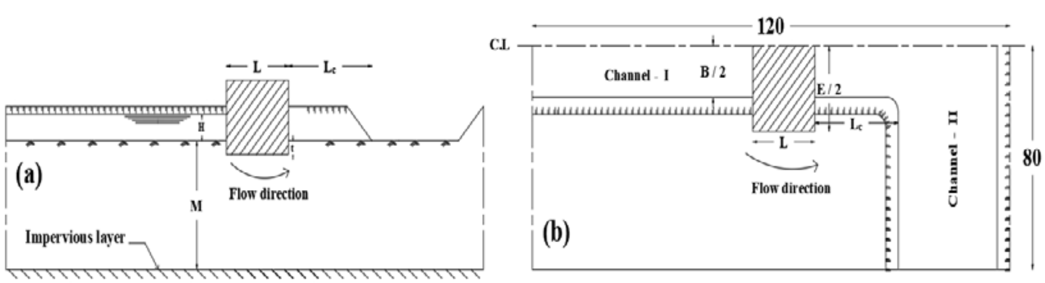

Fig. 1: Schematic sketch of the physical problem in the 3D verification (a) section elevation (b) half plan

Figure (2) show the effect of the relative location of the hydraulic structure, L_c/L, on the relative quantity of seepage around the structure, Q/KH^2, in which Q is the seepage flow rate, K is the permeability coefficient of the pervious foundation (taken here as 0.0001 m/sec) and H is the total head acting on the structure (taken constantly as 1.0 m). The figure indicates a good fit between the numerical model and Nasr's results in estimating the seepage quantity.

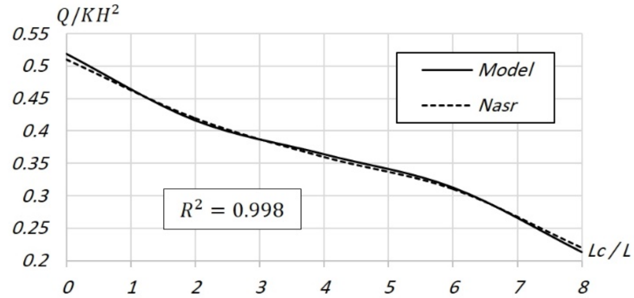

Fig. 2: Evaluation of the numerical model for estimating the 3D seepage quantity

Comparison of the numerical modeling results with the analytical and experimental results shows an acceptable good accuracy of the utilized numerical method to investigate the seepage flow characteristics under hydraulic structures.

3. Numerical Modeling

Different configurations of the cutoff walls driven under the floor of the structure resting on a pervious homogeneous isotropic soil of hydraulic conductivity, K = 0.0001 m/sec, and extended laterally to edges are analyzed. The depth of the cutoff wall under the structure, d, is consistent over the whole width of the structure as well as in the lateral direction and extends to the berm level on both sides of the structure. Figures (4-a, and b) show a schematic sketch of the problem. Here, H is the effective head of the structure, M is the thickness of the soil foundation layer, L is a structure length, E is the structure width, t is the structure thickness under the channel bed, L_s is the cutoff wall length in the lateral direction, and a is the distance of the cutoff wall from the upstream edge of the structure. The upstream canal length is $L_{u.s}$, the downstream canal length is $L_{d.s}$, and the side edge canal length is $L_{s.e}$. The following parameters are presented in a dimensionless form and kept constant for all runs: E/L=0.5, t/L=0.1, B/E=0.8, and H/L=0.1 while these variables are `varying as follows: the relative depth of the cutoff, d/L=0, 0.2, 0.4, 0.6, and 0.8, the relative upstream distance of the cutoff, a/L=0, 0.25, 0.5, 0.75, and 1.0, the relative length of the lateral cutoff, L_s/L=0, 0.25, 0.5, 1.0, and 2, and finally the relative thickness of the pervious layer, M/L=1, 1.5, 2, and infinite. The mesh of finite elements used in the analysis is a combination of a triangle, quadrilateral, and hybrid tetra meshing elements containing about 1,955,741 elements and 357,964 nodes.

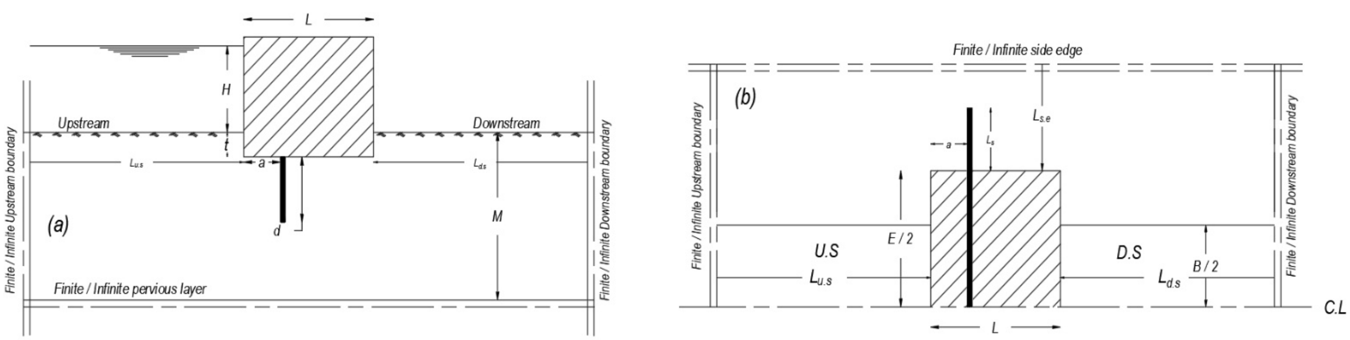

Fig. 4: Schematic sketch of the studied problem (a) elevation (b) half plan

4. Finite and Infinite Boundary Condition

During any analysis, assuming that the soil has a finite boundary in upstream, downstream, side edges, or the pervious layer boundary, as shown in figure (4), may not be appropriate or the correct approach as there is a substantial difference in the outcomes between the finite and infinite scenarios. To test this assumption, a simple example without any cutoff walls is worked out. In this case, the relative soil foundation thickness, M/L=1.0, the relative upstream canal length, $L_{u.s}/L$=1.50, relative downstream canal length, $L_{d.s}/L$=1.50, and relative side edge canal length, $L_{s.e}/L$=2. Two different boundary conditions are considered: Finite and infinite boundaries. The result obtained indicates that the seepage quantity and exit gradient for the case of using infinite boundaries increase by about 45%, and 7%, respectively. However, the uplift pressure didn't considerably change. The difference in the flow path between the two cases is shown in Fig. (5).

So, in the upcoming analysis, the upstream, downstream, and side edges boundaries are taken as infinite boundaries, while the horizontal boundary (pervious layer boundary) is varying as illustrated before.

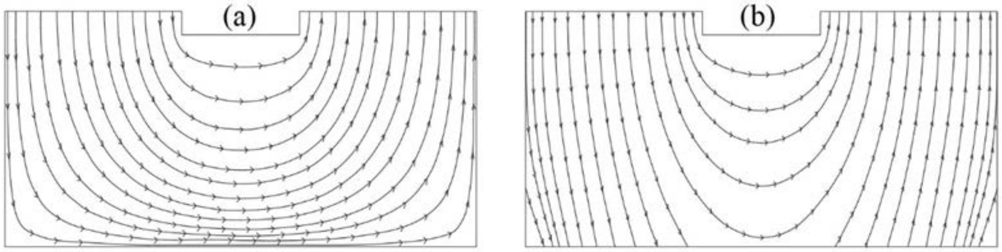

Fig. 5: Elevation view of the seepage path for different boundary conditions (a) finite (b) infinite

5. Analysis of Results

5.1. Case of (*M* = *L*)

5.1.1. Seepage Discharge

Without any cutoffs, the quantity of seepage discharge underneath and around the structure increases by about 541% more than the case without lateral seepage (i.e., 3D analysis has a seepage rate 541% more than 2D analysis).

Comparing the effect of cutoff wall depths located at the upstream end (a/L=0), it is found that if d/L=0.2, and 0.8 then the corresponding value of Q/KH^2 = 4.68, and 4.62, respectively, a reduction in the seepage flow rate that is not remarkable. On average for the ranges studied in the work, with an increase in the cutoff wall depth by 200% regardless of its location, the seepage rate decreased by 0.88%. In Fig. (6), the ratio of seepage rate in the presence of the cutoff wall, Q, to that in case no cutoff wall (reference value), Q_o, is plotted as a function of a/L, d/L, and L_s/L. From Fig. (6), it can be concluded that the best location for decreasing the seepage rate is by fixing the cutoff wall at either upstream or downstream end. However, using a cutoff wall in between the two ends increases the seepage rate, but this increase is dependent on the location of the cutoff wall. In general, increasing the cutoff wall depth reduces the seepage quantity, and increasing the lateral cutoff length also decreases the seepage rate but to a lesser extent. Also, as can be inferred from the figure that the maximum reduction of seepage rate reaches about 22 % when the cutoff wall relative penetration depth, d/L=0.8, relative lateral cutoff wall length, L_s/L=2, and relative cutoff position, a/L=1 (i.e., a/L=0 gives almost the same result). Note that, these relative parameters reach the maximum value for the current study which is obvious.

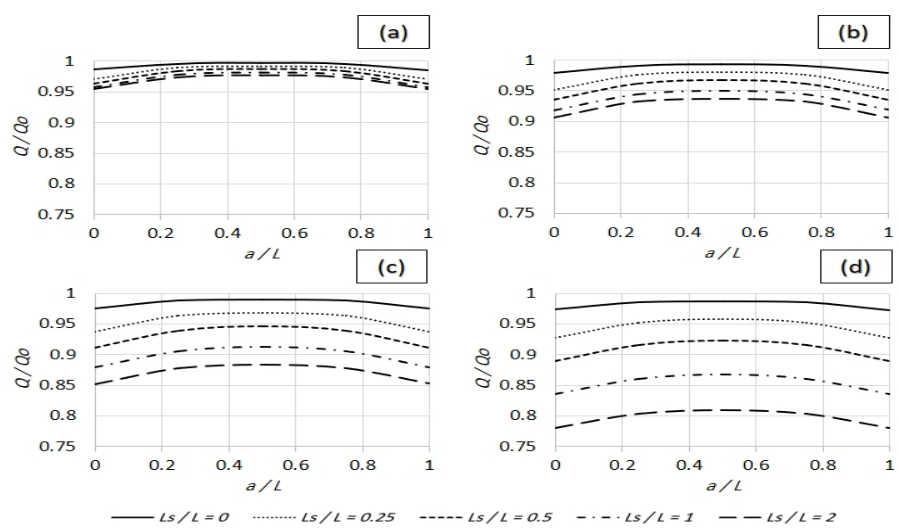

Fig. 6: Relative seepage quantity at different cutoff wall locations and depths (a) d/L=0.2 (b) d/L=0.4 (c) d/L=0.6 (d) d/L=0.8

5.1.2. Exit gradient at center-line

As a general criterion, the exit gradient increases while reducing the cutoff wall depth and the lateral cutoff length irrespective of its location. The best location for having the minimum exit gradient value is by fixing the cutoff wall at the downstream end of the floor. Figure (7) shows the relationship between the relative exit gradient, I_c/I_o, where I_c and I_o are the exit gradients at the centerline in the presence, and absence of the cutoff wall, respectively. Regardless of the lateral length of the cutoff, the exit gradient at the centerline of the structure has almost a negligible effect when the relative position of the cutoff wall is $a/L<0.75$. On the other hand, a notable decrease in its value is noticed as its relative position increases to 1.0 as shown in Fig. (7). Also, it can be noted that the maximum reduction in the exit gradient reached about 59% when the relative parameters reached their maximum values (i.e., d/L=0.8, L_s/L=2, and a/L=1).

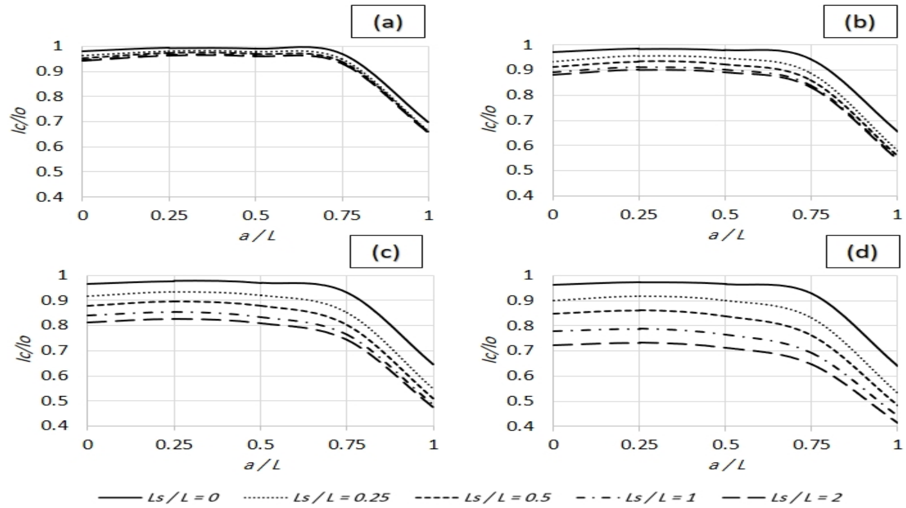

Fig. 7: Relative centreline exit gradient at different cutoff wall locations and depths (a) d/L=0.2 (b) d/L=0.4 (c) d/L=0.6 (d) d/L=0.8

5.1.3. Exit gradient at the edge

Generally, the exit gradient at the side edges of the structure is always more than that's at the centerline. And as before, the best location for having a minimum exit gradient at the edges is by fixing the cutoff wall at the downstream end. Without the use of the lateral cutoff wall, the exit gradient at the edge seems to be constant (i.e., a little variation is seen in Fig. (8) for the case of L_s/L = 0 may be due to the meshing size and skewness at the edge of the structure) even by changing the position of the cutoff wall underneath the structure. However, increasing the lateral cutoff length leads to a reduction in exit gradient value, and increasing its depth further enhances this reduction. It is found that the maximum reduction of exit gradient at the edge reached almost 54.7 % when the relative parameters reached their maximum values.

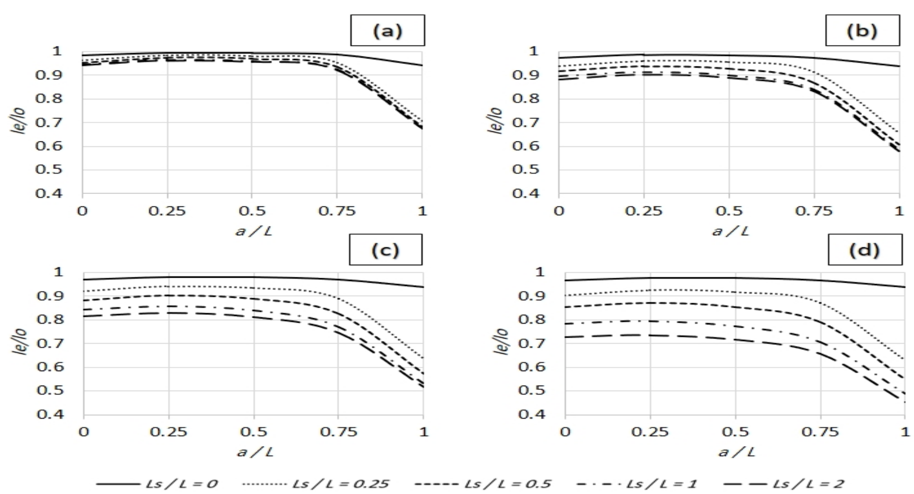

Fig. 8: Relative edge exit gradient at different cutoff wall locations and depths (a) d/L=0.2 (b) d/L=0.4 (c) d/L=0.6 (d) d/L=0.8

5.1.4. Uplift force

Figure (9) shows the relationship between the relative uplift force U/U_o, where U_o is the uplift force in the absence of a cutoff wall. From the figure, it can be noted that positioning the cutoff wall at the mid-length of the structure does not have any effect on the uplift compared to the referenced uplift force, U_o (i.e., results of the 3D analysis are the same in the absence and presence of cutoff wall). Shifting the cutoff wall to the left of the mid-length of the structure ($a/L < 0.5$) reduces the uplift force. Meanwhile, increasing the depth and lateral length of the cutoff further reduces the uplift force. The minimum uplift force reached about 37% for L_s/L=2 and d/L= 0.8. However, for this case, if the cutoff wall is positioned to the right of the mid-length (a/L>0.5), the uplift force increases. And the maximum uplift force (with a 37% increase compared to the reference value) occurs for L_s/L=2 and d/L=0.8.

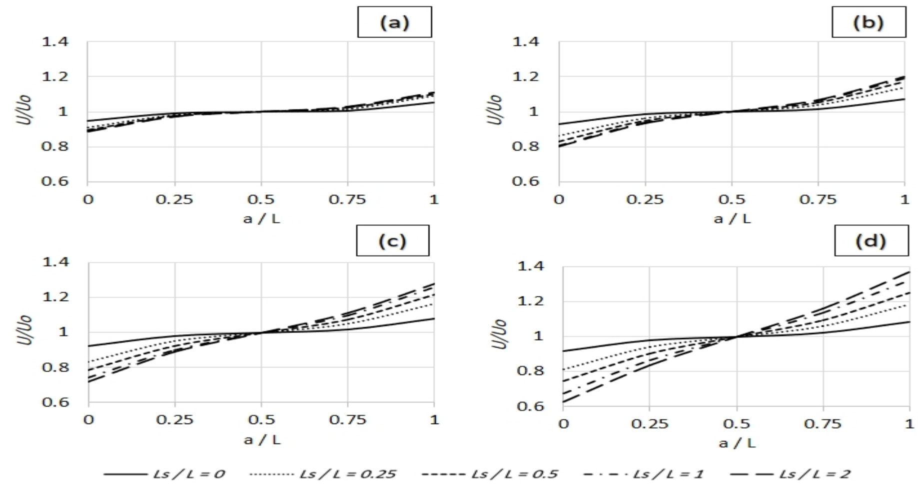

Fig. 9: Relative uplift force at different cutoff wall locations and depths (a) d/L=0.2 (b) d/L=0.4 (c) d/L=0.6 (d) d/L=0.8

5.2. Case of ($M > L$)

5.2.1. Seepage Discharge

Increasing the soil foundation thickness leads to an increase in the seepage quantity until the ratio M/L=2.18 where there is almost no further noticeable increase in its value and the change can be ignored. The quantities of seepage for the cases M/L=infinite, 2, and 1.50 are 23.5, 21.0, and 14.50%, respectively more than the case of M/L=1.

5.2.2. Exit gradient at center-line

Increasing the soil foundation thickness leads to an increase in the value of exit gradient at the centerline until M/L=2.27 where the change in its value may be neglected. The exit gradient at the center-line for the cases M/L=infinite, 2, and 1.50 are 6.9, 10.1, and 11.2%, respectively more than the case of M/L=1.

5.2.3. Exit gradient at the edge

Increasing the soil foundation thickness leads to an increase in the value of exit gradient at the edges. The exit gradient at the edges for the cases M/L=infinite, 2, and 1.50 are 2.7, 3.4, and 11.6%, respectively more than the case of M/L=1.

5.2.4. Uplift force

An increase in the value of the uplift force occurs with increasing the pervious soil foundation thickness if the relative distance of the cutoff wall, a/L, is less than 0.5 (i.e., the cutoff wall is fixed before the mid-length of the structure). And if the cutoff wall is fixed at the mid-length of the structure, there is no noticeable effect for the thickness of the pervious foundation on the uplift. However, fixing the wall after the mid-length of the structure (a/L>0.5) will result in decreasing the uplift force while increasing the thickness of the pervious foundation. The maximum increase in the value in the uplift force reached about 17.25% when the cutoff wall is at the upstream end of the structure with d/L=0.8 and L_s/L=2. While the maximum reduction in its value is about 8.4% when the cutoff wall is at the downstream end of the structure with d/L=0.8 and L_s/L=2.

6. Conclusions

A 3D analysis of seepage beneath and around hydraulic structures was carried out utilizing a cutoff wall as a control device. A parametric study for a wide range of variables was done and presented in a dimensionless form. From the results, the following main conclusions may be listed:

- The effect of using infinite boundaries is critical in the evaluation of the seepage characteristics beneath and around hydraulic structures. And it must be analyzed carefully during the design stage as the seepage quantity and exit gradient change significantly. However, the uplift force did not vary that much.
- The effect of using cutoff walls on seepage quantity is not that remarkable in the 3D analysis.
- The exit gradient increases while decreasing the cutoff wall depth or the lateral cutoff length regardless of its location. A dramatic decrease occurs when the position of the cutoff wall is more than 0.75 the length of the structure.
- Increasing the soil foundation thickness leads to an increase in the value of the seepage quantity, and the exit gradient until the relative thickness of the foundation to the structure length equals 2.18, and 2.27, respectively. Further increase in the thickness of the foundation does not show noticeable variation and the change may be ignored.
- An increase in the value of uplift force occurs with increasing the pervious soil foundation thickness when the cutoff wall is fixed before the mid-length of the structure. Fixing the cutoff wall at the middle of the structure does not show an apparent difference in the effect of foundation thickness. On the other hand, as the wall is shifted towards the downstream end, the effect of increasing the foundation thickness increases the value of the uplift force.

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