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EVALUATION RATIO OF SHEET PILE LENGTH AND DISTANCE EFFECTS SEEPAGE BENEATH CONCRETE DAMS USING SOFTWARE

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SUMMARY

Seepage through concrete dams plays an important role in the stability of the foundations due to the fact that high uplift pressures and exit gradients can cause piping, erosion, and ultimately the collapse of the structure. This research focuses on the effect of the position and the depth of the sheet piles on seepage in concrete dams employing a numerical method based on the finite element theory. The seepage model for the two-dimensional case was created by employing the software GeoStudio SEEP/W for investigating various placements of sheet piles for the steady-state flow problem. Three different situations of the dam foundations have been taken into account: without any sheet piles, with one sheet pile, and with double sheet piles. In total, 105 numerical simulations have been conducted to investigate the effect of the depth ratio and the location ratio of the sheet piles on exit gradient and uplift pressure distribution. The lowest value of the exit gradient was achieved by placing the sheet pile at the downstream end of the dam foundation with a penetration depth of about 60% of the foundation width. The minimum value of uplift pressure below the dam body was achieved by placing a single sheet pile at the upstream end with a small penetration depth ($d/B = 0.1$). Conversely, increasing the depth of a downstream sheet pile acts as a barrier that blocks the flow, thereby increasing the uplift pressure distribution beneath the main dam foundation. In the case of double sheet piles, the results showed that equal penetration depths yielded higher exit gradients than those with unequal depths. It is clear from the results presented that proper placement of sheet piles is very important in reducing seepage, hence ensuring the safety of the dam foundation.

Key words: *dam, exit gradient, finite element modeling, SEEP/W, uplift pressure.*

INTRODUCTION

One of the important factors that influences the performance of hydraulic structures is seepage underneath concrete dams [1]. Due to the differences in hydraulic head between the upstream and downstream areas, the seepage flow takes place through the foundation soils, causing excessive uplift pressures, high exit hydraulic gradient, internal erosion, and even possible failure of structures [2]. Hence, seepage flow control and reduction of hydraulic forces acting underneath the dam foundation are important aspects in order to ensure the safe performance of such structures [3]. Seepage flow control methods, especially cutoff walls and sheet piles, are often used to achieve longer seepage paths and reduce hydraulic pressure acting underneath the concrete dam foundation [4]. Such methods are mainly influenced by geometrical properties of such barriers and depend on penetration depth, position, and arrangement in the foundation soil.

Modeling methods for the evaluation of seepage behavior using numerical modeling methods involving the finite element method have been very useful due to the complexity involved. Numerical seepage analysis using computer software gives an opportunity for the evaluation of alternative designs and determination of key parameters such as exit gradient and uplift pressure [5]. While many investigations have been carried out on the subject of cutoff walls and methods of seepage control, very few have taken into consideration the effect of depth and location of the sheet piling wall through a parametric investigation [6]. The present study is aimed at developing a two-dimensional finite element model using SEEP/W for this purpose.

The specific aims of this research include:

- To examine the effect of sheet pile depth and placement on exit gradient and uplift pressure.
- To examine the seepage behavior of various sheet pile placements, such as the single and double sheet pile arrangements.
- To determine an appropriate sheet pile arrangement for minimizing seepage under dam foundations.

The rest of the paper is organized as follows. Literature review about seepage analysis under hydraulic structures, cutoff walls, sheet pile systems, and numerical modeling is described in Section 2. Section 3 discusses the proposed numerical modeling technique, involving SEEP/W based finite element method, soil parameters, and governing equations. Section 4 introduces the parameters used in the simulations and the process of validation. The results of numerical analysis are described in section 5, including the effect of sheet pile position and depth on the exit gradient and uplift pressure, sensitivity analysis, and design recommendations for seepage prevention. Finally, section 6 concludes the research.

LITERATURE REVIEW

Studies dealing with seepage under hydraulic structures have traditionally used an approach for the evaluation of seepage path length, uplift pressure, and exit gradient [8]. Such an approach gives fundamental knowledge about the behavior of groundwater flow under the hydraulic structure. However, analytical studies usually use simplified assumptions and lack the ability to describe complicated conditions in the foundation and different designs of the cutoff wall. A number of investigations concerning the behavior of seepage have been done by means of analytical and numerical studies [9]. An approach related to the use of creep theory and weighted seepage paths was created in order to estimate seepage resistance under hydraulic structures. Further investigation showed the application of mathematical solutions for cutoff walls and seepage under the foundation; the results proved the significance of cutoff wall depth and location for the control of hydraulic forces [11][13]. The finite element numerical methods using software packages like GeoStudio SEEP/W and PLAXIS are becoming popular for seepage analysis in hydraulic structures because of their capability of modeling complicated shapes of foundations and hydraulic boundary conditions [12]. Using SEEP/W, it was

shown that cutoff wall inclinations, location, and penetration depths have a significant effect on seepage flow behavior [15].

Research on inclined cutoff walls indicated that the direction and position of the wall affect seepage performance and can enhance the hydraulic behavior. The optimization technique has also been used in finding appropriate locations and designs of cutoff walls for minimizing risks associated with seepage [14][19]. Studies using various soil types and cutoff wall arrangements have demonstrated the importance of the combination of upstream and downstream control in seepage reduction [16]. Nonetheless, previous research was mostly performed on single parameters such as cutoff wall inclination, soil heterogeneity, or position of walls. There have not been many systematic evaluations of the effects of both sheet pile depth and its position based on numerous numerical simulations. Additionally, a comprehensive parametric study for various sheet pile arrangements with identical hydraulic conditions is lacking. This study fills this gap in research and creates a SEEP/W-based finite element model involving 105 simulation cases in order to analyze the effect of sheet pile depth ratio and position ratio on exit gradient and uplift pressure below concrete dams.

NUMERICAL MODELING METHODOLOGY

For the numerical modeling, Geo-Slope (SEEP/W) software was used. The numerical modeling was conducted in order to investigate the water flow regime beneath the dam foundation and determine the seepage behavior. Geo-Slope (SEEP/W) software was used for steady-state analysis. The dam geometry, axes, and profile are presented in figure 1. The model geometry consists of the floor length (B) and two sheet piles with depths d_1 and d_2 , defined by the foundation depth (D) and the head difference (H). The numerical analysis was carried out via GeoStudio SEEP/W 2022 R2, which uses the finite element method (FEM) to solve groundwater seepage problems. The steady-state saturated seepage analysis was adopted to determine the effect of the sheet pile length and position on seepage characteristics underneath the dam foundation [17]. The numerical domain was divided into four-node triangular finite elements for representing the soil foundation and boundary conditions. The solver configuration involved the application of the Newton–Raphson iteration algorithm with the convergence criteria being 1×10^{-5} and the number of iterations 100 per solution step. Geometry of the SEEP/W model and its finite element discretization are shown in figure 1 and figure 2. The first figure demonstrates the conceptual two-dimensional model of seepage with boundary conditions and location of sheet pile, whereas the second one demonstrates the finite element mesh of the dam foundation with sheet piles.

Domain discretization was performed with finite elements via triangulation, where four-node elements were utilized. Element size was around 2 m^2 . The meshing approach was selected in such a way that the accuracy of the simulation results related to seepage behavior in the soil foundation is guaranteed, in accordance with GEO-SLOPE (2012). Steady state was presumed in this case, and the model domain was completely saturated for all simulation times [18]. GeoStudio SEEP/W (version 2022 R2) was applied for numerical modeling by the method of finite elements for steady-state seepage analysis. Solver settings include 1×10^{-5} convergence criteria and up to 100 iterations per step with the Newton-Raphson iterative method [20].

Soil Properties and Model Assumptions

Input parameters were given in the model to set the hydraulic conditions. Conductivity at the interface between dam and sheet pile materials was assumed to be zero due to their impermeable nature. The domain of soil was considered homogeneous, isotropic, and completely saturated. Values of hydraulic conductivity were considered as $k_x = k_y = 1 \times 10^{-5} \text{ m/s}$, and the weight of water was considered as 9.81 kN/m^3 . Structural deformation of the foundation of the dam was ignored in the modeling process to study the seepage problem only. Soil foundation was considered as a homogeneous sandy clay layer to provide a common platform to study the influence of sheet pile configurations. The key assumptions that have been made during the numerical analysis include steady-state seepage conditions, isotropic hydraulic conductivity ($k_x = k_y$), fully saturated soil conditions, and insignificant deformations in the dam-foundation system. All these assumptions will enable the analysis to concentrate solely on the seepage control performance of various sheet pile configurations. The value of the hydraulic

conductivity was determined on the basis of the permeability values of sandy clay soils and past seepage modeling analyses presented in table 1 below.

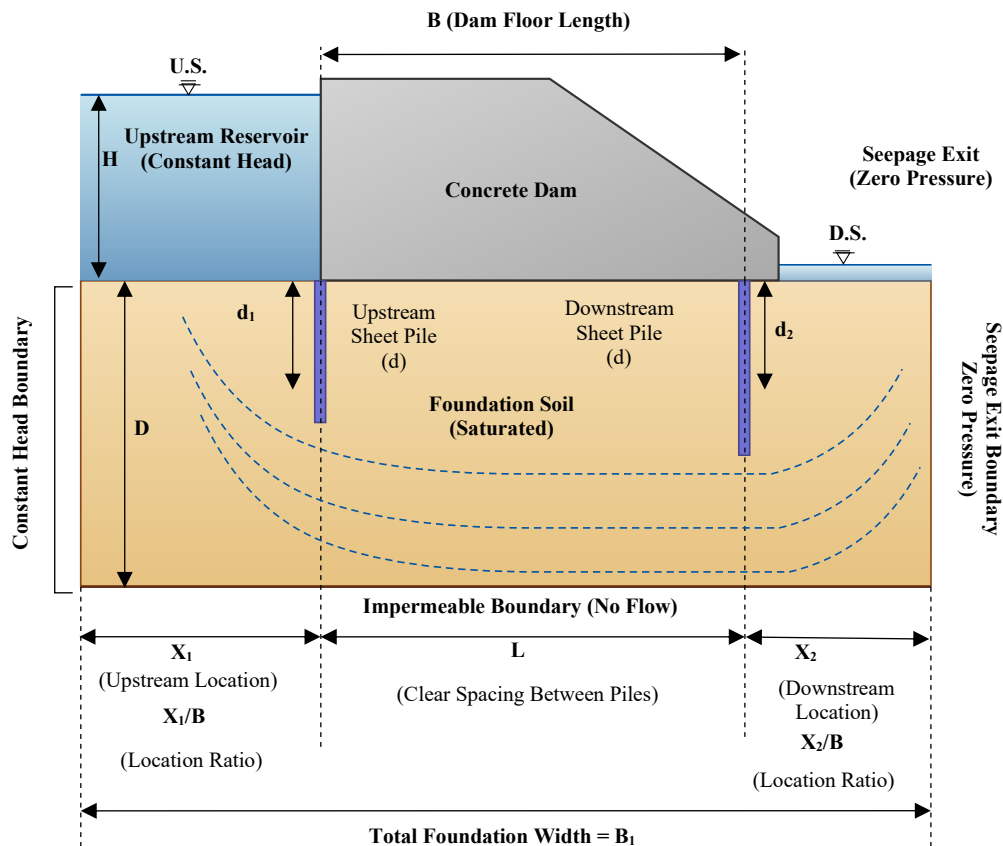


Figure 1. Two-Dimensional finite element model configuration showing dam foundation, boundary conditions, and sheet pile arrangements used in SEEP/W seepage analysis

Table 1. Soil and numerical model parameters

Parameter	Value	Unit
Soil type	Sandy clay	-
Hydraulic conductivity (kx, ky)	1×10^{-5}	m/s
Unit weight of water	9.81	kN/m ³
Porosity	45	%
Saturated condition	Fully saturated	-
Soil behaviour	Homogeneous isotropic	-

Fully saturated conditions were assumed for the foundation soil since the problem involved studying the steady state seepage characteristics around the concrete dam. This makes it possible to determine the distribution of hydraulic heads, exit gradients, and uplift pressure on the soil.

The seepage flow through the foundation of the dam was modeled using mathematical equations governing the flow of saturated groundwater. The seepage discharge velocity according to Darcy's law is given by the following equation:

$$q = -k \nabla h \quad (1)$$

Where in equation (1) q is Darcy seepage velocity, k is hydraulic conductivity, and h is hydraulic head.

The continuity equation for steady-state seepage is written as follows in equation (2):

$$\nabla(k \nabla h) = 0 \quad (2)$$

The value of the exit hydraulic gradient that indicates possible soil erosion and piping is given by:

$$i = \frac{\Delta h}{L} \quad (3)$$

Where Δh and L in equation (3) are the hydraulic head difference and seepage path length, respectively. The uplift pressure acting under the foundation of the dam was calculated using:

$$P_u = \gamma_w h \quad (4)$$

Where P_u , γ_w , and h in equation (4) represent the uplift pressure, unit weight of water, and hydraulic head, respectively. These are the mathematical fundamentals of the finite element seepage analysis carried out by SEEP/W.

Boundary Conditions and Numerical Domain Definition

The constant head condition was used because of the presence of water in the reservoir. Boundary conditions for Dirichlet and Neumann types were imposed on the boundaries of the dam for better simulation of hydraulics. Upstream boundary of the reservoir was modeled by applying the Dirichlet boundary condition with a constant head equal to $H = 10$ m. The downstream boundary was modeled by applying a zero-pressure boundary condition corresponding to the free discharge of water. The lower boundary of the computational domain was assumed to be impermeable and modeled with a Neumann no-flow boundary condition.

Parametric Simulation Design

A performance analysis has been conducted for three types of models:

1. The original dam without sheet piles
2. Single sheet pile model
3. Double sheet piles

Totally, 105 models have been developed by changing the values of the depth ratio of sheet piles ($d/B = 0.1, 0.3, 0.5, 0.7$) and location ratio of the sheet piles ($x/B = 0, 0.1, 0.3, 0.5, 0.7, 1$). The combination of $d1, d2, x1$, and $x2$ for double sheet piles is considered due to its interaction effect (See table 2).

Table 2. Parametric simulation matrix

Case	Sheet Pile Configuration	Depth Ratio (d/B)	Location Ratio (x/B)	Number of Simulations	Output
1–24	Single upstream/downstream pile	0.1, 0.3, 0.5, 0.7	0, 0.1, 0.3, 0.5, 0.7, 1.0	24	Exit gradient / Uplift pressure
25–104	Double sheet piles	0.1, 0.3, 0.5, 0.7	Different combinations of x_1/B and x_2/B	80	Exit gradient / Uplift pressure
105	Selected final configuration	0.7	1.0	1	Exit gradient / Uplift pressure

The considered dimensionless parameters (d/B and x/B) have been picked due to their common usage in the range previously adopted in the seepage studies of the hydraulic structures. The application of normalized depths and locations allows the results to be generalized with regard to various dam shapes without reference to a particular scale. In the parametric simulation matrix, there were 105 SEEP/W simulations of both single and double sheet piles. The depth ratios (d/B) considered in the analysis included 0.1, 0.3, 0.5, and 0.7, whereas location ratios (x/B) ranged between 0 and 1.0. Table 2 shows simulation parameter values used in this study. Each experiment yielded two primary output parameters: hydraulic gradient at the exit point and uplift pressure.

The datasets of exit gradient and uplift pressure were collected from all simulation cases, giving a total of 105 numerical data points to be used in comparison [7]. The mesh independence test was performed based on the application of course, medium, and fine meshes. The chosen mesh had variations less than 0.5% when compared to the fine mesh for exit gradient, showing convergence and numerical stability [10]. The following boundary conditions were used: a fixed value of upstream head (Dirichlet condition, $H = 10$ m) was set at the reservoir boundary, while a zero-pressure value (Dirichlet condition) was imposed at the downstream boundary. An impermeable boundary condition (Neumann condition) was used at the base of the model, while no-flow boundaries were used at sheet piles. Steady-state simulations were done with all the cases using the finite element solution technique.

Mesh Independence and Numerical Validation

A mesh of 721 nodes and 647 elements was created, as depicted in figure 2 below.

A mesh independence study was conducted to confirm the validity of the numerical prediction. Three levels of mesh density, including coarse, medium, and fine mesh, were developed and analyzed depending on the change in the exit gradient value. The use of medium mesh with 647 elements yielded less than 0.5% error compared to the fine mesh result. Thus, it became necessary to conduct any further mesh refinement, and the chosen mesh was used in all further simulations.

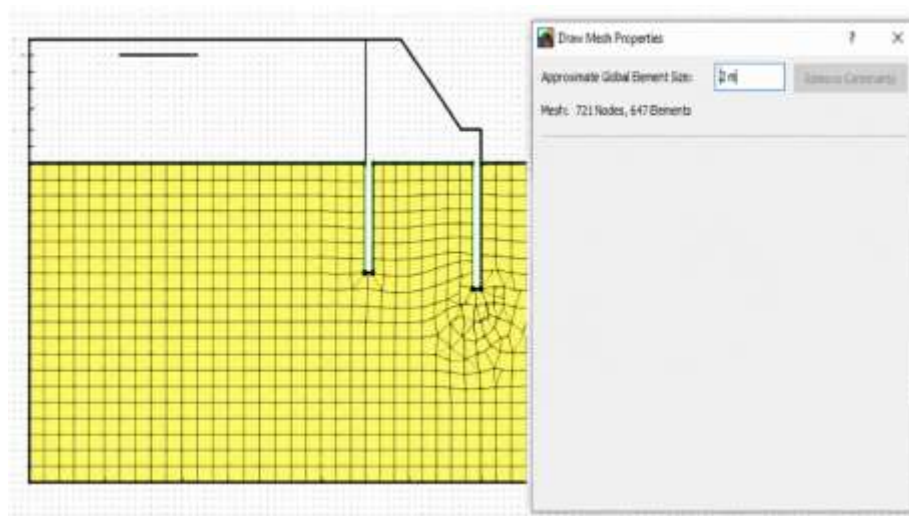


Figure 2. SEEP/W finite element discretization for the dam foundation with sheet pile configurations

EXPERIMENTAL SETUP

Model Validation and Verification

Considering that this current study is based on numerical modeling, the process of validation involved numerical verification and comparison with existing seepage theories. The analysis of the predicted seepage behavior was done considering the basic concepts of groundwater flow along with the already existing analytical methods.

The relationship between the decrease in exit gradient and the increase in the length of the seepage path, along with the influence of sheet piles on uplift pressure as per the seepage theory, was observed in the present results. The results show that the newly formed SEEP/W model effectively simulates the seepage physical behavior.

In comparison to the traditional analytical method, the proposed FEM approach gives a better understanding of the seepage flow behavior due to the complicated geometry of sheet piling. The parametric study carried out in this paper offers further information about the optimal design of the sheet piles, which is presented in table 3.

Table 3. Comparison of present FEM approach with existing seepage analysis methods

Method	Approach	Advantage	Limitation
Bligh Method	Analytical creep theory	Simple preliminary estimation	Does not consider detailed soil behavior
Lane Method	Weighted creep theory	Improved seepage path evaluation	Limited applicability for complex geometry
Khosla Theory	Analytical solution	Suitable for hydraulic structures	Requires simplified assumptions
Previous FEM Studies (SEEP/W, PLAXIS-based seepage models)	Numerical finite element modelling	Improved seepage prediction	Limited parameter investigation
Present Study (SEEP/W 2022 R2)	FEM-based steady-state seepage analysis	Evaluates 105 sheet pile configurations	Depends on numerical assumptions

Table 4 shows the numerical modeling parameters used in this paper to simulate the seepage in the GeoStudio SEEP/W program. The seepage analysis was carried out using the steady-state seepage module with the use of the Newton-Raphson iterative solver in order to get the stable solutions of the seepage problem. Convergence tolerance value of 1×10^{-5} and maximum number of iterations equal to 100 were used in the analysis. The seepage domain was meshed using four-node triangular finite elements in an amount of 647 elements.

Table 4. Numerical simulation settings

Parameter	Value
Software	GeoStudio SEEP/W
Version	2022 R2
Analysis type	Steady-state seepage
Solver	Newton-Raphson
Iteration limit	100
Convergence tolerance	1×10^{-5}
Element type	Four-node triangular
Elements	647

Sensitivity Analysis of Sheet Pile Parameters

Correlation coefficient:

$$R = \frac{Cov(x, y)}{\sigma_x \sigma_y} \quad (5)$$

From equation (5), sheet pile depth had more impact on the exit gradient than the location ratio.

Analysis and Discussion of Results

Effect of Sheet Pile Depth and Location Ratios

A sensitivity analysis was done to determine the impact of the sheet pile depth ratio (d/B) and location ratio (x/B) on seepage parameters. This can be viewed from table 5 below.

Table 5. Influence of sheet pile parameters on seepage performance

Parameter	Variation Considered	Effect on Exit Gradient	Effect on Uplift Pressure
Sheet pile depth ratio (d/B)	0.1–0.7	Decreases with increasing depth	Increases slightly
Upstream location ratio (x/B)	0–1.0	Moderate influence	Reduces uplift pressure
Downstream location ratio (x/B)	0–1.0	Reduces exit gradient	Limited influence

Relative sensitivity for each parameter was determined by the percent change in exit gradient and uplift pressure. It is noted that sheet pile depth has a stronger influence on the exit gradient, whereas the sheet pile's location dictates its effect on uplift pressure. An upstream sheet pile cuts off hydraulic head early,

reducing uplift pressures downstream of it across the base. In contrast, a downstream sheet pile creates a damming effect, building up uplift pressure beneath the concrete foundation.

The major parameters have a great impact on the exit gradient and uplift pressure. In this research, 105 cases were simulated by using the computer simulation model with $H = 10$ m, $B = 15$ m, $D = 30$ m, and an isotropic soil of ($\frac{k_x}{k_y} = 1$). Four different ratios of depth were studied: $d/B = 0.1, 0.3, 0.5$, and 0.7 times the floor length. At every ratio of depth, investigation was carried out at different locations of sheet piles with location ratios of $x/B = 0, 0.1, 0.3, 0.5, 0.7$, and 1.0 . The major parameters under consideration are the exit gradient and uplift pressure.

The effect of the Position of a Sheet Pile on The Exit Gradient and Uplift Pressure

The relationship between sheet pile location ratio and exit hydraulic gradient for different penetration depths is presented in figure 3. The results indicate that increasing the sheet pile location ratio reduces the exit gradient due to the extension of the seepage flow path and the reduction of hydraulic energy concentration near the downstream region. The effect becomes more significant at higher sheet pile penetration depths.

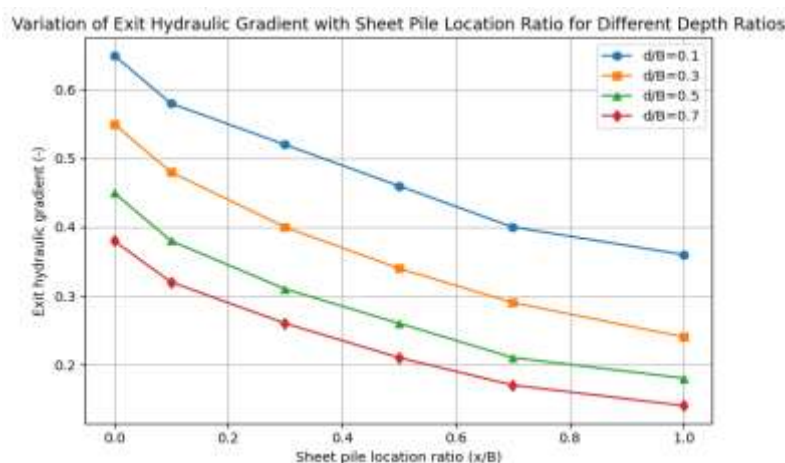


Figure 3. Variation of exit hydraulic gradient with sheet pile location ratio for different sheet pile depth ratios

Variation of uplift pressure with respect to sheet pile location ratio at various penetration depths is presented in figure 4. It is evident from the results that the placement of sheet pile on the upstream side is more beneficial for uplift pressure control due to the modification of hydraulic heads beneath the dam foundation.

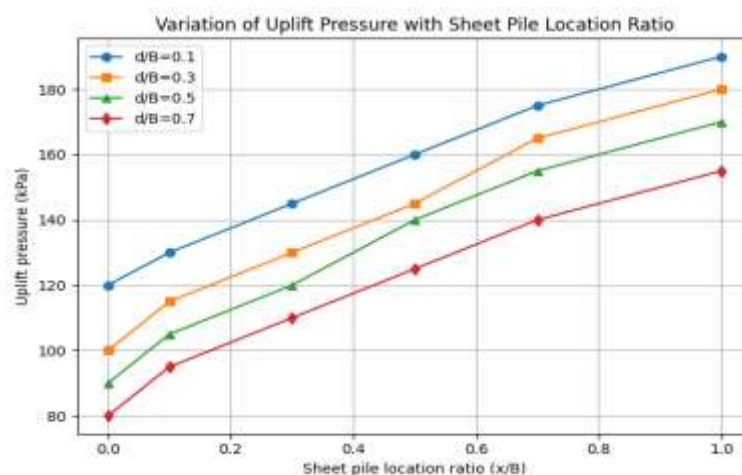


Figure 4. Variation of uplift pressure with sheet pile location ratio for different sheet pile depth ratios

The Effect of the Depth of Sheet Pile Ratio on Exit Gradient and Uplift Pressure

The influence of sheet pile depth ratio on exit hydraulic gradient is shown in figure 5. An increase in the penetration depth increases the effective seepage length; thus, the exit gradient decreases. The minimum value of the exit gradient is observed for the maximum sheet pile depth ratio under investigation.

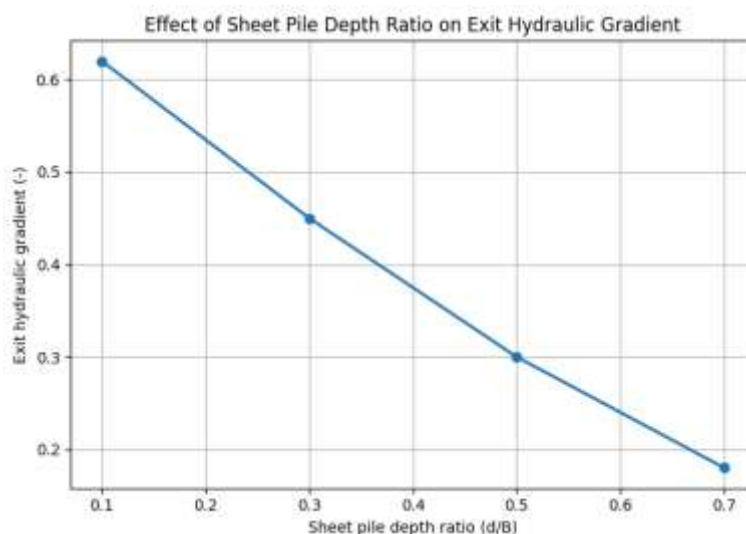


Figure 5. Effect of sheet pile depth ratio on exit hydraulic gradient

Influence of depth ratio on the distribution of uplift pressures for a single sheet pile configuration is shown in figure 6. It can be observed that when a sheet pile is placed near the downstream toe, increasing the depth ratio d/B from 0.1 to 0.7 causes the uplift pressures under the dam floor to become higher due to flow restriction. When placed at the upstream heel, increasing depth successfully reduces downstream uplift pressures.

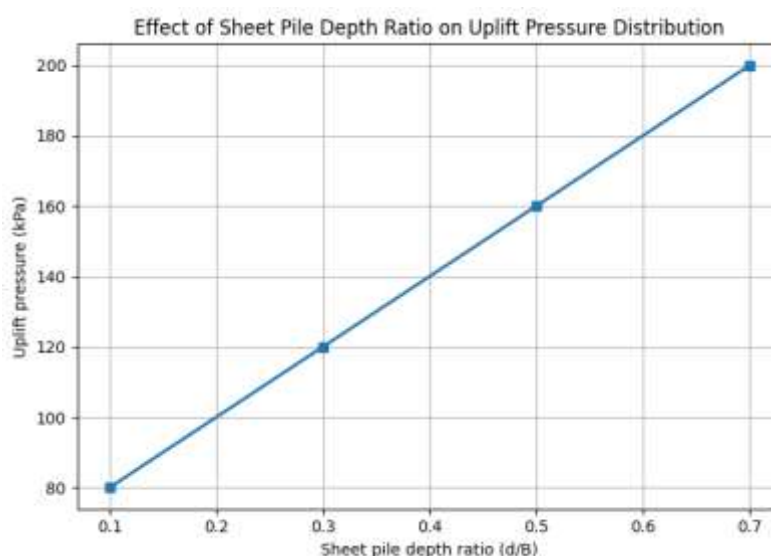


Figure 6. Effect of sheet pile depth ratio on uplift pressure distribution for single upstream sheet pile configuration

The Effect of the Exit Gradient of Two Sheet Piles

The combined effect of the second sheet pile on the exit hydraulic gradient is presented in figure 7. From the results, it can be seen that an increase in penetration depth of the second sheet pile helps in reducing the exit gradient.

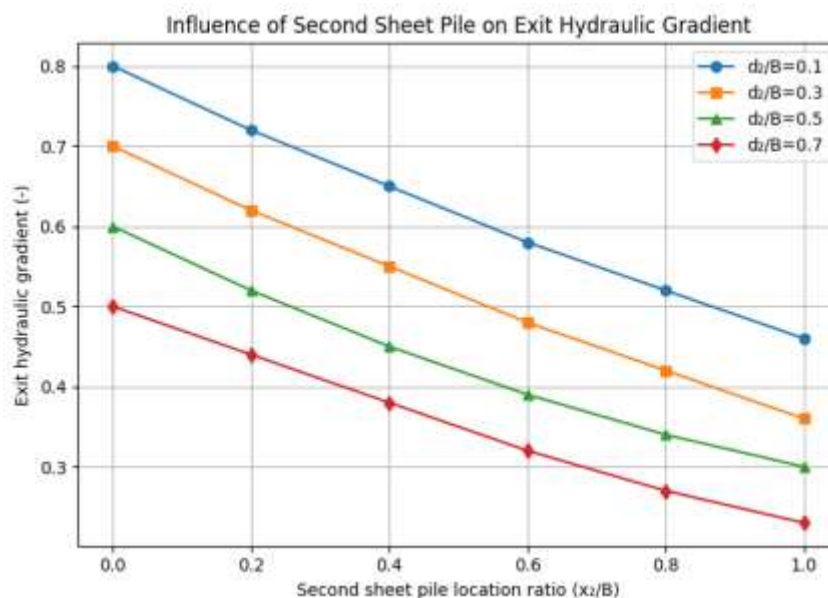


Figure 7. Influence of second sheet pile depth and location on exit hydraulic gradient

The Effect Rate of d_1/d_2 on the Exit Gradient

The effect of the relative depth of sheet pile ratio (d_1/d_2) on the exit gradient was studied for the case of double sheet pile systems and presented in figure 8. It is observed that the exit gradient is maximum when both the sheet piles have penetration depths equal to each other ($\frac{d_1}{d_2} = 1$). As soon as the depth ratio is not one (whether increased or decreased), the exit gradient value is reduced owing to better interruption of seepage paths. This shows that the different penetration depths of sheet piles can be more effective than those having the same penetration depths.

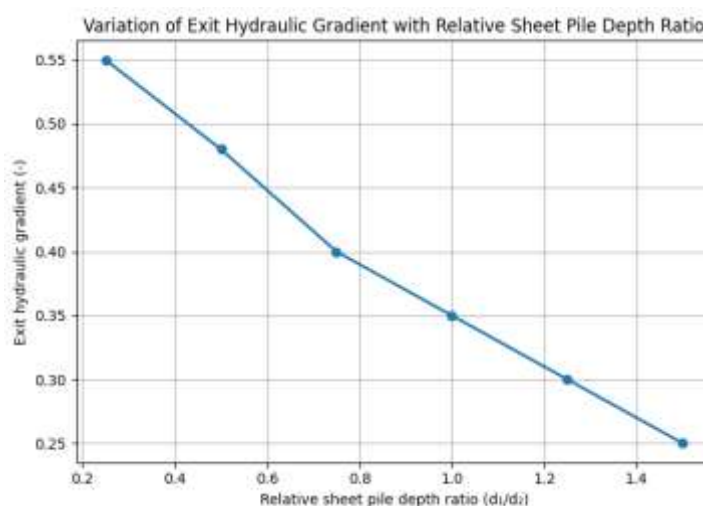


Figure 8. Influence of relative sheet pile depth ratio (d_1/d_2) on exit hydraulic gradient

From the numerical findings, it can be concluded that sheet piles affect the seepage behavior under the concrete dams. With an increase in the depth of the sheet pile, there is a subsequent increase in the seepage path length, leading to better management of the exit gradient. However, deep penetration may cause uplift pressure distribution under the foundation of the concrete dam. Consequently, the design of sheet pile for the reduction of seepage should be a trade-off between seepage reduction and uplift pressure management. These findings give practical information on how to select the sheet pile ratio in the applications of seepage reduction under concrete dams. According to the parametric study findings, when selecting sheet pile configurations, one must take into account the two factors, namely seepage

reduction and uplift pressure management. From the findings, it can be seen that sheet piles located upstream manage to reduce uplift pressure, while those downstream reduce the exit gradient. Hence, a combined design considering sheet pile ratio and position is suggested to improve seepage safety under concrete dams.

CONCLUSION

In this paper, a numerical method using the finite element method was adopted to determine the effects of the sheet pile location and depth on seepage performance around concrete dams. It was found that the configuration of the sheet pile affects the exit hydraulic gradient and uplift pressure distribution. This study showed that increasing the values of sheet pile location and depth ratios causes the exit gradient to decrease due to an increased seepage flow path and a decrease in hydraulic energy concentration near the downstream zone. However, it must be emphasized that the depth effect is highly dependent on location: increasing the depth of an upstream sheet pile reduces uplift pressure under the dam floor, whereas increasing the depth of a downstream sheet pile leads to the development of a higher uplift pressure distribution under the foundation. This research indicated that placing the sheet piles upstream is more favorable in terms of reducing uplift pressure, but the downstream location of sheet piles is more appropriate concerning the control of the exit gradient. The best condition for decreasing the exit gradient was found for $\frac{x_l}{B} = 1$ with $d/B = 60\%$. In the case of a downstream single sheet pile system, the minimum uplift pressure under the dam floor was observed at the smallest value of the depth ratio under consideration ($d/B = 0.1$) because deeper downstream piles block water escape. Conversely, for an upstream pile system, deeper penetration is more favorable for mitigating uplift pressure across the foundation base. According to the results obtained for the two-sheet pile system, the maximum exit gradient was recorded in the case where the penetration depth of the two piles was the same ($d1/d2 = 1$); however, different depth ratios provided better seepage reduction. In general, the conclusions drawn from this research highlight the importance of choosing an appropriate sheet pile location and depth in order to optimize seepage reduction effectiveness and ensure safe and stable functioning of concrete dam foundations.

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