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CONTROL OF SEEPAGE IN MULTI-LAYERED SOIL UNDER HEADING-UP STRUCTURES USING VERTICAL AND INCLINED SHEET PILES

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ABSTRACT

Using sheet piles under the floor of a heading-up structure decreases the flow rate, uplift force, and hydraulic gradient, and increases the structure's safety. The type of soil under the structure is an important factor in the seepage analysis. In this study, a 2D numerical model is used to simulate the flow under the floor of a heading–up structure resting on two soil layers of unequal thicknesses. The floor is considered to have vertical and inclined sheet piles with different configurations. The model was first verified using experimental data from a previous research, then applied to study different scenarios for the thicknesses and hydraulic conductivities of the soil layers. Various locations and inclination angles of the sheet piles are also studied. The study highlights the effect of the soil layers thicknesses and characteristics on the efficiency of the sheet piles in reducing the flow rate, uplift force, and exit gradient. The results show that such soil properties have a great effect on the efficiency of sheet piles. It is strongly recommended to consider the effect of the soil characteristics as well as the thickness of the upper soil layer relative to the sheet pile's depth in the floor's design.

KEYWORDS: Heading-up structures; Seepage; SEEP2D; Soil characteristics; Vertical and inclined sheet piles.

التحكم في التسرب داخل التربة متعددة الطبقات تحت منشآت الحجز باستخدام قواطع رأسية و مائلة

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الملخص

استخدام قواطع تحت فروشات منشآت الحجز يقلل كمية المياه المتسربة وقوة الدفع على الفرش والميل الهيدروليكي مما يزيد من أمان المنشأ. نوع التربة تحت المنشأ عامل مهم جداً في تحليل التسرب. في هذه الدراسة تم استخدام نموذج عددي ثنائي الأبعاد لتمثيل السريان بالتسرب تحت منشآت الحجز القائمة على تربة مكونة من طبقتين غير متساويتين. تم اعتبار وجود قواطع رأسية ومائلة تحت فرش المنشأ. تم أولاً التحقق من النموذج العددي باستخدام بيانات معملية من دراسة سابقة ثم استخدامه لدراسة حالات أخرى مختلفة لسُمك و خصائص التربة تحت المنشأ. كما تم أيضاً دراسة أماكن وزوايا مختلفة للقواطع الموجودة تحت المنشأ. توضح هذه الدراسة تأثير سُمك و خصائص طبقات التربة على كفاءة القواطع في تقليل كمية السريان تحت المنشأ و ضغط الرفع على الفرش و انحدار خروج الماء. تبين النتائج أن سُمك و خصائص طبقات التربة لها تأثير كبير على كفاءة القواطع تحت المنشأ. توصي الدراسة أن يتم الاهتمام بخصائص و سُمك الطبقة العليا من التربة بالنسبة إلى عمق القاطع أثناء تصميم فرش منشأ الحجز.

الكلمات المفتاحية : منشآت الحجز، التسرب ،النموذج العددي SEEP2D، خصائص التربة ، قواطع رأسية ومائلة.

1. INTRODUCTION

Seepage is a vital factor that affects the stability of heading-up structures. The hydraulic gradient of the water seeping under a heading-up structure can threaten its stability. Excessive uplift pressure underneath the structure and piping downstream the structure are some forms of seepage threats. Using sheet piles (cut-offs) under the floor of heading-up structures increases the percolation length, and consequently, decreases the flow rate, hydraulic gradient, and uplift pressure. Many experimental and numerical methods can be used to simulate the seepage problems. Experimental modeling such as sand tanks and electric analogue models are widely used in confined seepage analysis. 2D and 3D numerical models such as finite element, finite difference, and boundary element models are also very common. The numerical models are usually validated using experimental data [1].

The effects of vertical single and multiple sheet piles (cut-offs) under the floors of heading up structures on the flow rate, uplift, and exit gradient have been evaluated in many previous studies. El-Molla [2] investigated seepage under the aprons of hydraulic structures founded on isotropic soil and provided with a single cutoff using SEEP2D model. The model was found to be a precise tool for estimating the percolation length and the effect of each face of the cutoff. Mobasher [3] used an electrolytic tank to investigate the effect of the two faces of a single cutoff under the apron of a heading up structure on the hydraulic gradient. Jamel [4] used SEEP/W model to evaluate the effect of using upstream and downstream vertical sheet piles in two equal soil layers. Rasool [5] used ANSYS model to discuss the effect of the mutual interference between sheet piles on the uplift pressures and exit gradient. One layer of homogenous isotropic soil and three vertical sheet piles under the structure were considered. El Molla et al. [6] studied the head loss along vertical sheet piles fixed at the ends of a heading up structure's apron using SEEP2D model. Abdelaal et al. [7] investigated the effect of using vertical sheet piles under the apron of a heading-up structure on the efficiency of the apron's horizontal length using SEEP2D for a single homogeneous soil layer. El Molla et al. [8] analyzed the horizontal path of the creep line between vertical cutoffs using SEEP2D and electric analogue models, considering two equal horizontal soil layers under the structure.

Al Tabatabaie & Al Waily [9] used an electrical analogue model to study the efficiency of the front and rear faces of vertical cutoffs in dissipating the energy of the percolating water. The studied hydraulic structure was formed on a single homogeneous soil layer. Shousha et al. [10] used an experimental sand tank model and SEEP/W numerical model to investigate the effect of using a grouted vertical barrier on the seepage characteristics under small hydraulic structures formed on a single layer of soil. Salmasi et al. [11] used SEEP/W model to investigate the effect of double vertical cutoffs under hydraulic structures. The location and depth of the cutoffs were varied. The foundation of the structure was considered as a single, homogeneous, and isotropic soil layer. Some researchers also studied seepage under heading up structures with vertical sheet piles as a 3D problem considering the effect of the flow through the banks [12–15]. All the 3D studies considered that the structure is formed on a single soil layer.

Other researchers investigated different cases of inclined single and double sheet piles. Alsenousi and Mohamed [16] analyzed a dam with a single inclined sheet pile and the resulting uplift, seepage discharge, and exit gradient for steady and unsteady conditions. The optimum inclination angle was also evaluated considering a single layer of homogeneous isotropic and anisotropic soil under the structure. Obead [17] used a 2D finite element numerical model to study the seepage underneath a dam formed on a single homogeneous soil layer, with a single inclined cut-off at different locations and angles. Mansuri et al. [18] used SEEP/W model to study the effects of different angles and locations of a single inclined cutoff on the seepage characteristics. Moharrami et al. [19] investigated the effect of different cut-off systems on the uplift pressure and piping using SEEP/W. They varied the inclination angle, length, and position of a single cutoff. The spacing between multiple vertical cutoffs, and their number were also considered. Khalili Shayan and Amiri-Tokaldany [20] used an experimental model along with Geostudio model to evaluate the effects of a single inclined cut-off's angle on the uplift force, seepage discharge, and exit gradient. Alnealy [21] used a sand tank model to study seepage through three soil layers of equal depths under a hydraulic structure's foundation with vertical and inclined cutoffs.

Alghazali & Alnealy [22] used a seepage tank to study seepage through a single layer of soil under a hydraulic structure with single and double inclined cut-offs. Alnealy & Alghazali [23] used SLIDE program to analyze seepage under hydraulic structures formed on a single soil layer and its effect on the structure's safety considering a single inclined cut-off at the upstream or the downstream, or double cutoffs at both sides together. Hussein et al. [24] used SEEP2D model and an electrolytic tank to evaluate the percolation length for aprons that are founded on a single layer of isotropic soil and provided with one inclined cutoff with different inclination angles. Bakr et al. [25] used a quadrature element method to study the effect of the position and inclination angle of a cut-off for a homogenous isotropic soil layer under a concrete dam. Elmolla et al. [26] investigated the effect of using a single inclined cutoff under a hydraulic structure on dissipating the creep line's energy using SEEP2D model. The structure was founded on a single soil layer. Salim and Othman [27] studied the effect of using an inclined intermediate sheet pile besides the upstream and downstream piles and its inclination angle using SEEP/W program. Armanuos et al. [28] studied the effectiveness of inclined double cutoff walls under hydraulic structures formed on a single soil layer. They considered the effect of the upstream and downstream cutoffs' depths, locations, and inclination angles using SEEP/W numerical model.

The literature review shows that the previous studies considered that the heading up structure is either resting on a single soil layer or on multiple layers of equal thicknesses. Varying the foundation soil layers' thicknesses and characteristics and evaluating their effects on the efficiency of the vertical and inclined sheet piles have not been considered before as far as the authors know. In this research, SEEP2D finite element numerical model is used to simulate seepage under the floor of a heading–up structure resting on two horizontal soil layers of unequal thicknesses. Different scenarios for the thicknesses and hydraulic conductivities of the soil layers under the floor are considered. The floor is considered to have various cases of vertical and inclined sheet piles at different locations. The effect of the soil layers thicknesses and characteristics on the seepage discharge, uplift force, and exit gradient is evaluated for vertical and inclined sheet piles at different locations and inclination angles. The numerical model is verified using experimental data from a previous research by Shousha et al. [10].

2. MATERIALS AND METHODS

2.1. DIMENSIONAL ANALYSIS

The variables involved in the study are defined in the nomenclature section (at the end of the paper), shown in **Fig. 1**, and functionally presented as:

$$\emptyset(K_1, K_2, T_1, T, \theta, X, q, q_o, H, d, \rho_w, \mathrm{L}, \mathrm{F}, F_o, E, E_o, \mathrm{g}) = 0 \qquad \text{Equation (1)}$$

Applying Buckingham's π Theorem lead to the following dimensionless π terms:

$$\emptyset(\theta, \frac{q}{K_1 H}, \frac{q_o}{K_1 H}, \frac{d}{H}, \frac{T_1}{H}, \frac{T}{H}, \frac{L}{H}, \frac{X}{H}, \frac{K_2}{K_1}, \frac{F}{H K_1^2 \rho_w}, \frac{F_o}{H K_1^2 \rho_w}, E, E_o) = 0 \qquad \text{Equation (2)}$$

The water head on the structure (H), the sheet pile's depth (d), the floor' length (L), the total thickness of the soil under the floor (T), the density of water (ρ_w), and the gravitational acceleration (g) are considered constant throughout the study. Relating the thickness of the upper soil layer (T_1) to the sheet pile's depth (d), the location of the sheet pile (X) to the length of the floor (L), and the hydraulic conductivity of the upper soil layer (K_1) to that of the lower soil layer (K_2), the functional relationship is reduced to:

$$\emptyset\left(\theta, \frac{q}{K_1 H}, \frac{q_o}{K_1 H}, \frac{T_1}{d}, \frac{X}{L}, \frac{K_1}{K_2}, \frac{F}{H K_1^2 \rho_w}, \frac{F_o}{H K_1^2 \rho_w}, E, E_o\right) = 0 \qquad \text{Equation (3)}$$

Relating the seepage discharge, the uplift force, and the exit gradient of all scenarios to those of the reference case, the π terms final functional relationship becomes as follows:

$$\emptyset\left(\theta, \frac{q}{q_o}, \frac{T_1}{d}, \frac{X}{L}, \frac{K_1}{K_2}, \frac{F}{F_o}, \frac{E}{E_o}\right) = 0 \qquad \text{Equation (4)}$$

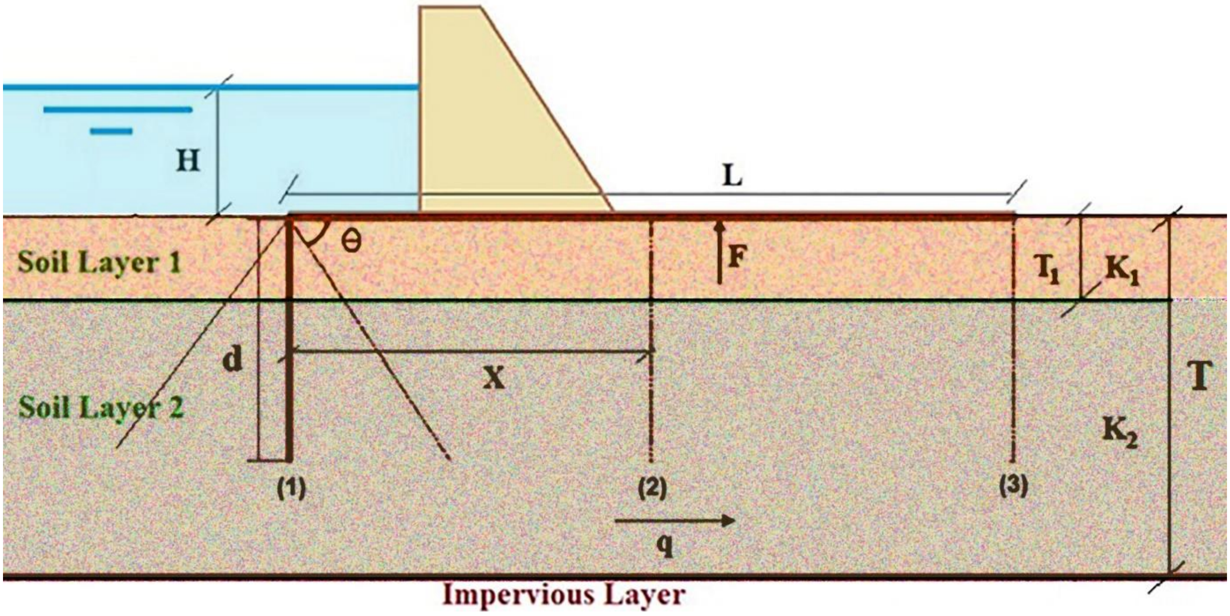

Fig. 1: The variables involved in the study.

2.2.DESCRIPTION OF THE NUMERICAL MODEL

SEEP2D is a 2D finite element steady state numerical model that is used to solve vertical profile seepage problems. Its governing equation is the Laplace equation [29]. A series of tasks are performed in sequence to perform a run on SEEP2D model. First, the geometry of the studied problem is entered to SEEP2D to define the regions of different materials. After that, the polygons of the different regions are built. Next, a finite element mesh is constructed. Initial runs are performed using different mesh cell sizes to select the ideal cell size that attains accurate results without unnecessary computations. In the present study, the optimum mesh size was found to vary from 3m in the seepage field to 1m at the sheet piles as shown in **Fig. 2**.

Next, the hydraulic conductivities of the different regions are entered (refer to **Fig. 3**). After that, the boundary conditions are applied to the mesh. The boundary conditions in this study are the total effective water head (H) at the upstream, which is considered to have a constant value of (10 m), and the total effective water head (H) at the downstream, which is considered to have a constant value of (0 m). After the model is set up, it is executed to calculate the head, total flow rate, discharge velocity, and pore water pressure at every node in the mesh. Finally, the results are viewed as the contours of the equipotential total heads, the velocity vectors, the flow lines, and the total flow rate. After viewing the solution, the results are checked and evaluated to see if they are reasonable. If the results need enhancement, the mesh is refined, or the input coefficients are altered, and a new solution is computed. A sample of the model's results is displayed in **Fig. 4**.

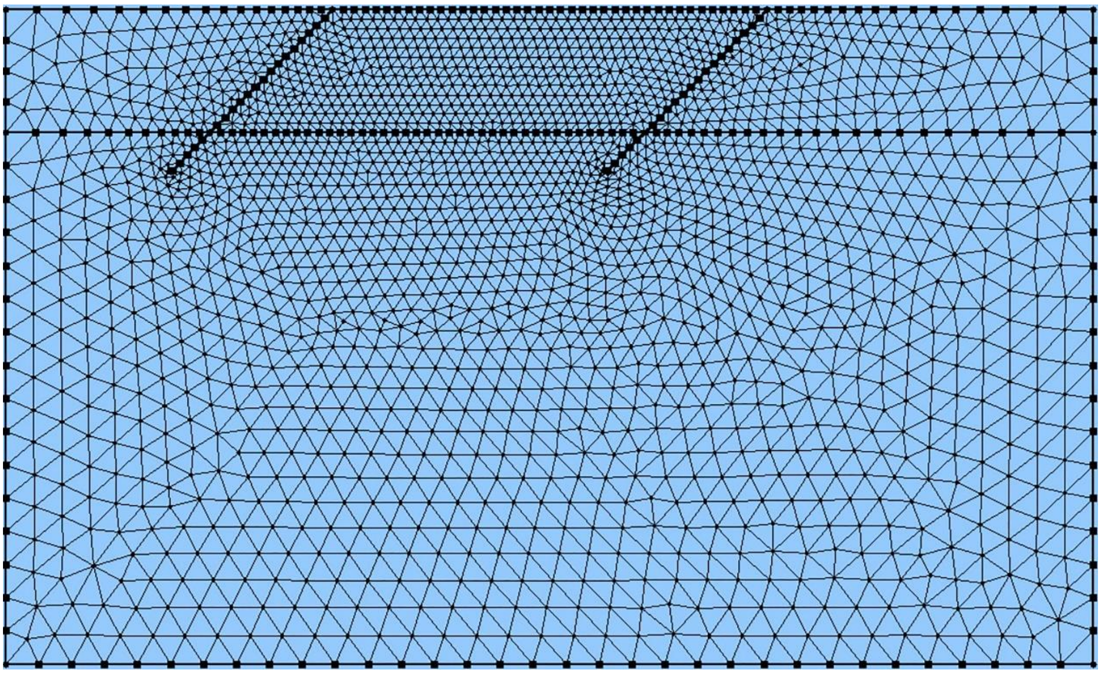

Fig. 2: The finite element mesh under the floor and around the sheet piles.

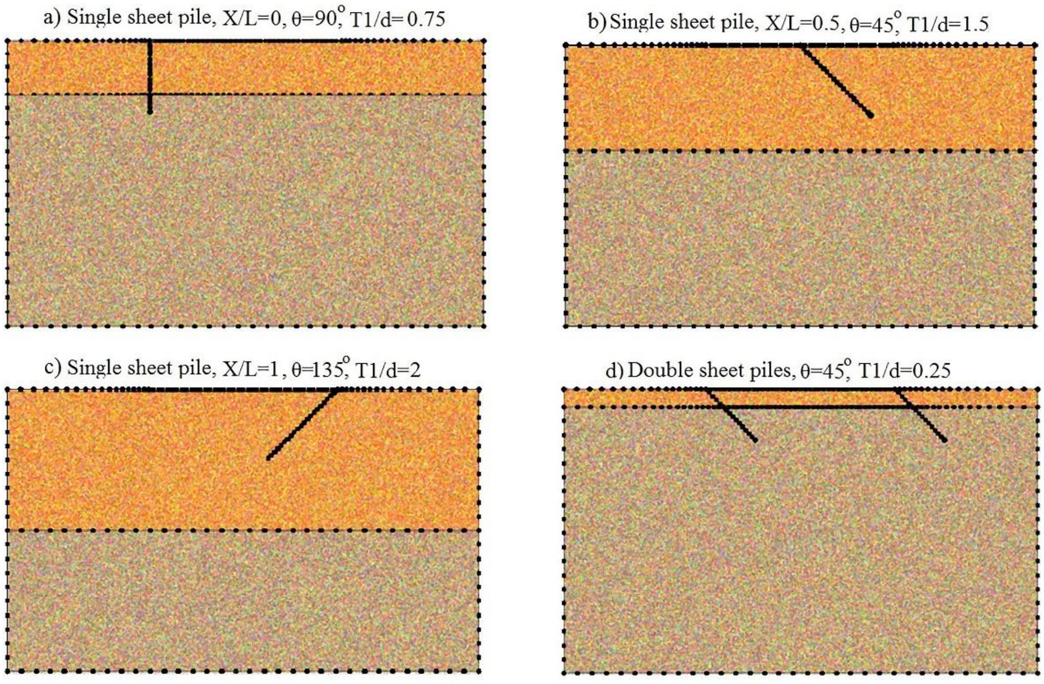

Fig. 3: Sample of the studied soil layers scenarios for different sheet piles configurations.

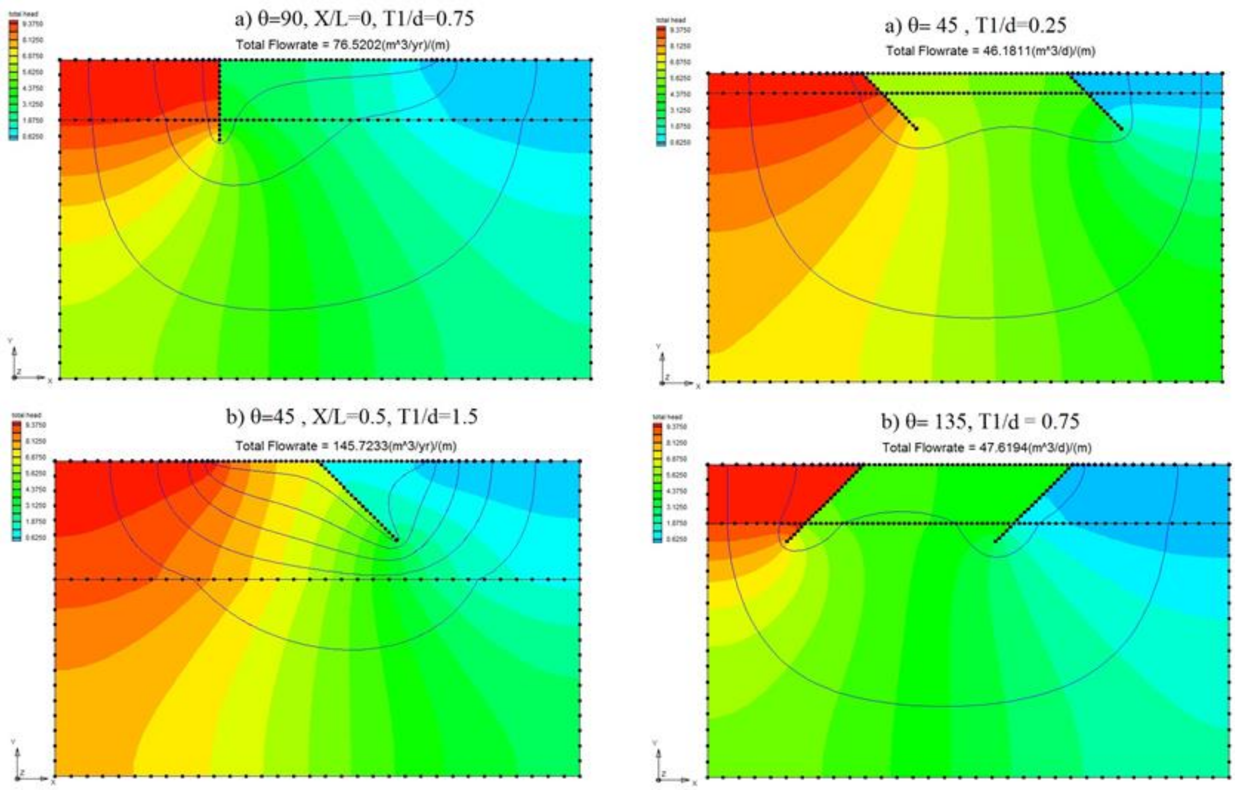

Fig. 4: Sample of SEEP2D results.

2.3.VERIFICATION OF THE NUMERICAL MODEL

The numerical model was verified by experimental observation performed in a previous study by Shousha et al. (2020) . 15 numerical runs have been performed to verify the numerical model. The soil under the structure was taken as a homogenous and isotropic single soil layer. The floor of the heading–up structure has a length (L) of 40 m. The total thickness of the soil under the floor (T) is 60 m with a hydraulic conductivity (K) of 44.44 m/ day. The studied depths of the sheet pile (d) are 15m, 20m, and 40m. The relative position of the sheet pile (X/L) is 0, 0.25, 0.5, 0.75, and 1. The thickness of the sheet pile (b) is 5 cm. The upstream water head is 10m while water head at downstream side is Zero (dry downstream). **Fig. 5** shows the cross-section of the heading-up structure used in the model's verification.

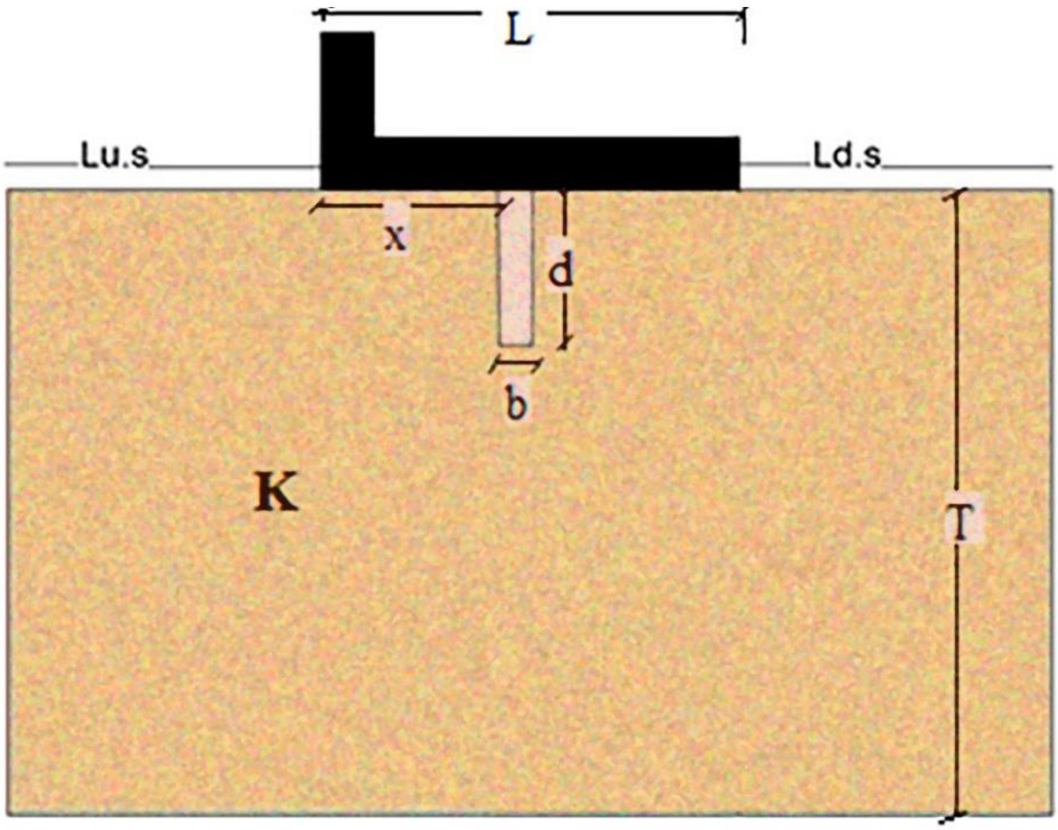

Fig. 5: Cross-section of the heading-up structure used in the model's verification.

In order to verify SEEP2D numerical model, the ratio between the results of each sheet pile scenario and the reference case are calculated and compared to those obtained from the previous experimental study by Shousha et al. [10]. The coefficient of determination (R^2) is used to evaluate the performance of SEEP2D model compared to the experimental results. R^2 measures how close the data is to a fitted regression line. The value of R^2 approaches 0 for very far fitted data and 1 for perfectly fitted data [30]. The coefficient of determination (R^2) for the regression line of perfect matching between the previous experimental results and SEEP2D results (y = x) equals 0.9 for the seepage discharge results, 0.93 for the uplift force results, and 0.95 for the exit gradient results (refer to **Fig. 6**). Hence, the SEEP2D model's accuracy is considered very good and can be relied on to study further scenarios.

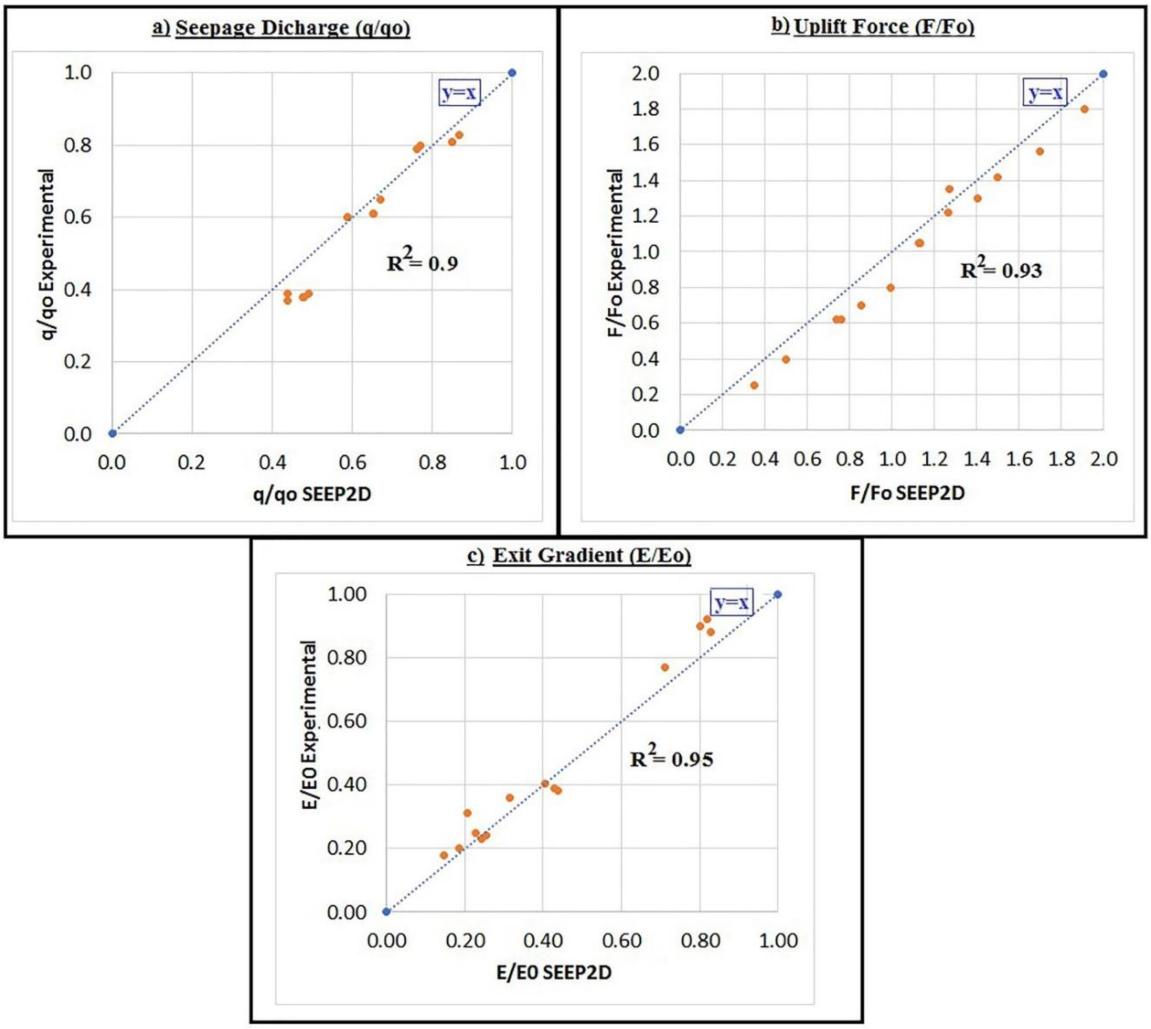

Fig. 6: Results of SEEP2D model verification for: a) seepage discharge, b) uplift force, c) exit gradient.

2.4.THE NUMERICAL MODELING SCENARIOS

In this study, SEEP2D model is used to simulate seepage under the floor of a heading–up structure formed on two horizontal soil layers of unequal thicknesses. The floor is considered to have sheet piles at different locations and inclination angels. The effect of the soil layers thicknesses and hydraulic conductivities on the efficiency of sheet piles is evaluated. The studied dimensions are selected to be the same as the experimental model by Shousha et al. [10] to verify the model, as explained in the previous section. After the model's verification, it is applied to investigate various scenarios of soil layers thicknesses and hydraulic conductivities, and sheet piles locations and inclination angles. The upstream water head (H) is taken as 10m in all the studied scenarios. The total depth of pervious soil layer under the floor is 30 m divided into two layers of hydraulic conductivities K_1 and K_2, where K_1 is the hydraulic conductivity of the upper layer and K_2 is the hydraulic conductivity of the lower layer. The floor's length is 40 m and provided with a single sheet pile of a depth (d) equals 15 m, or two sheet piles with equal depths of 15 m located at the floor's ends.

The reference case considers that the structure is founded on a single layer of homogenous isotropic soil with no sheet piles. All the variables are examined in the form of dimensionless ratios. Three sheet pile positions are studied (X/L) = 0.00, 0.50, and 1.00. Six scenarios are studied for the upper soil layer's thickness ratio (T_1/d) = 0.25, 0.5, 0.75, 1, 1.5, and 2.00. The angle of the sheet pile's inclination (θ) is also varied to 45°, 90°, and 135°. The various sheet piles configurations are studied considering a single homogeneous soil layer and two unequal soil layers of $K_1/K_2 = 4$ under the structure's floor. In order to evaluate the effect of the soil layers hydraulic conductivity ratio (K_1/K_2) on the results, the case of single vertical upstream sheet pile (X/L=0 and θ =90°) is also studied for K_1/K_2 = 0.02, 0.04, 0.1, 0.25, 10, 25, and 50. For each scenario, the seepage flow rate, uplift force, and exit gradient are calculated. **Fig. 7** shows the numerical modeling scenarios. A total number of 92 runs have been performed throughout the study.

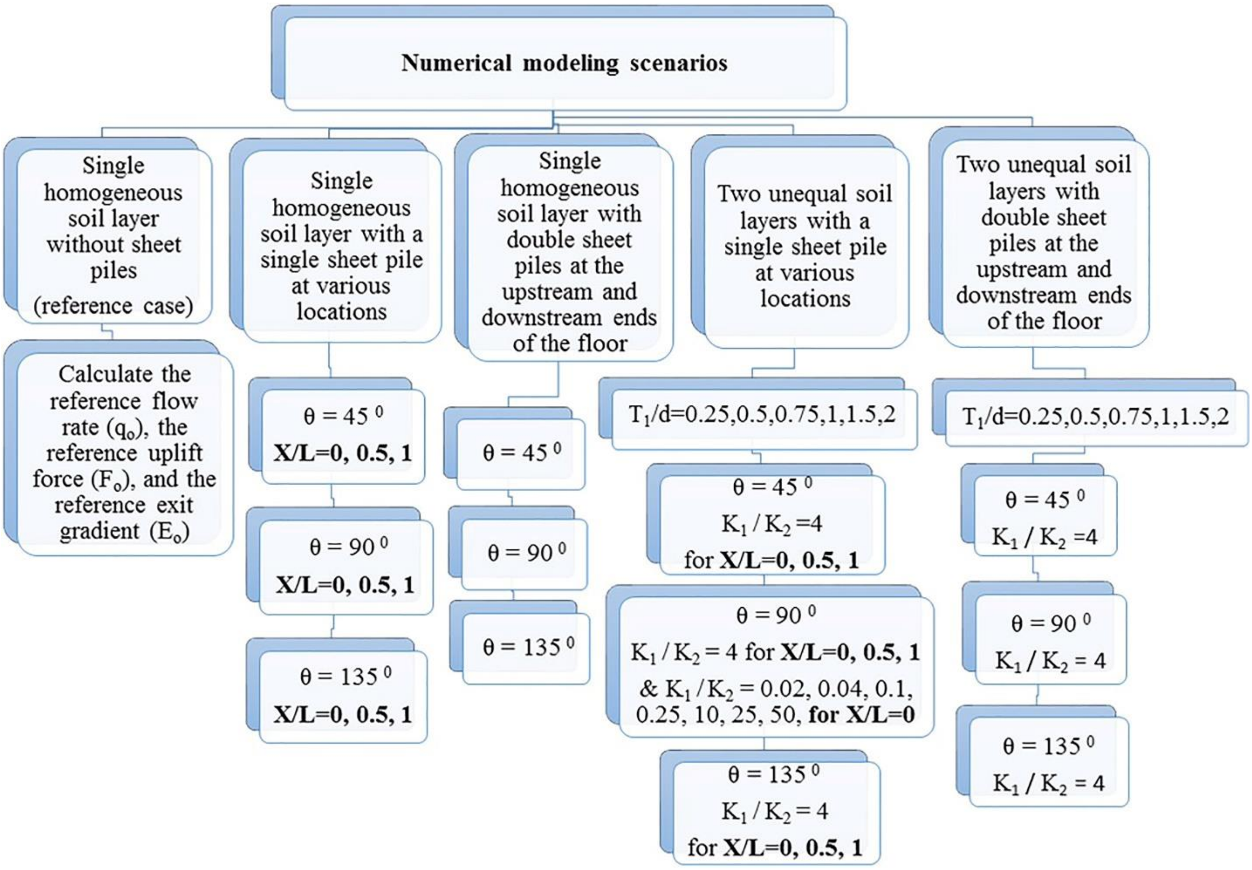

Fig. 7: The numerical modeling scenarios.

3. RESULTS AND DISCUSSION

3.1.THE EFFECT OF SOIL LAYERS THICKNESSES ON THE SEEPAGE DISCHARGE.

Fig. 8 shows the results of the seepage discharge ratio (q/q_o) for a single homogenous soil layer under the floor with different sheet piles configurations. The case of double sheet piles at the floor's ends showed the best performance in reducing q/q_o, especially for inclined sheet piles with $\theta = 45^o$ and $\theta = 135^o$ which showed a less seepage discharge ratio (q/q_o=0.45) than the case of vertical sheet pile ($\theta = 90^o$), which resulted in q/q_o= 0.53. This can be attributed to the longer percolation length that the seeping water takes in the cases of $\theta = 45^o$ and $\theta = 135^o$.

Fig. 8 also shows that when using a single sheet pile under the floor is necessary, the most efficient configuration in reducing the seepage discharge is the upstream end inclined sheet pile (X/L=0) with an angle of $\theta = 135^o$ and the downstream end inclined sheet pile (X/L=1) with an angle of $\theta = 45^o$. These two sheet pile configurations resulted in q/q_o= 0.5 which is very close to the result of double inclined sheet piles located at the floor's ends (q/q_o =0.45). This can be because the sheet pile's inclination in these directions at the floor's ends adds an extra horizontal length to the floor and causes the seeping water to move a longer distance. On the contrary, the case of vertical single sheet pile located at the middle of the floor (X/L=0.5) resulted in the highest seepage discharge ratio (q/q_o= 0.72). And accordingly, this sheet pile configuration (X/L=0.5) is not recommended to be used.

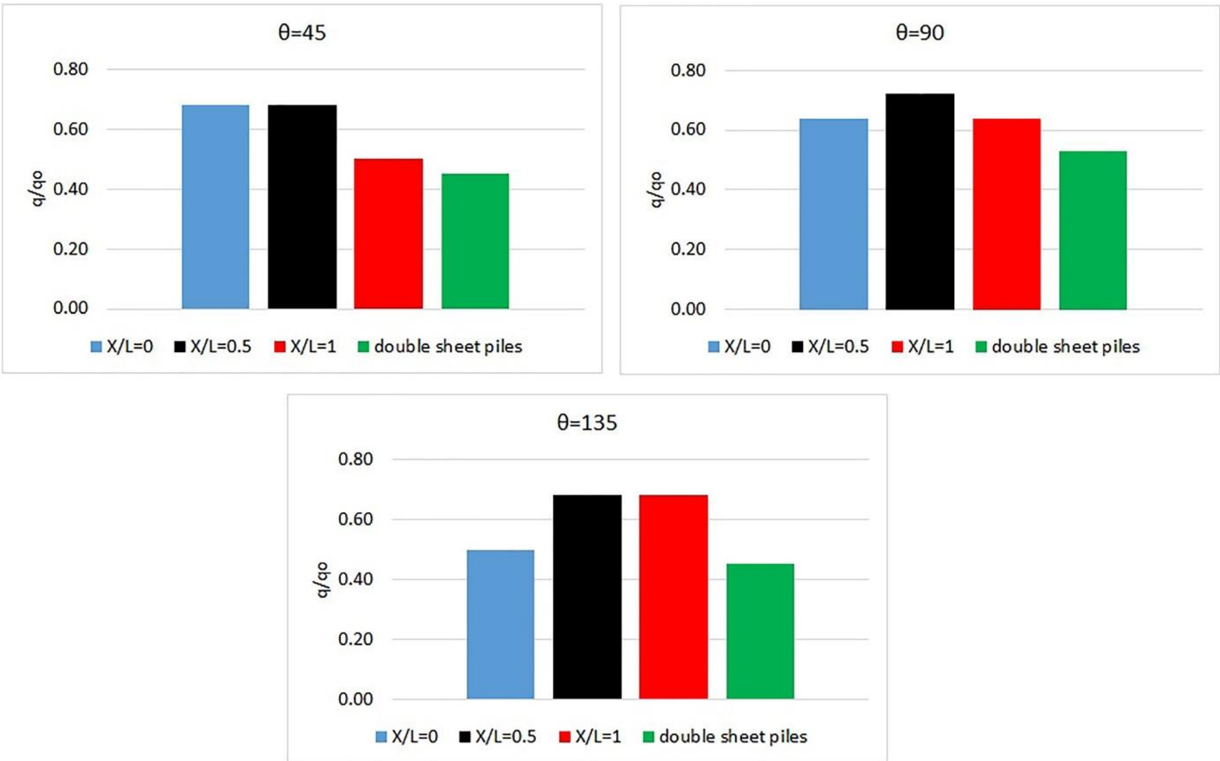

Fig. 8: q/q_o for different sheet piles angles and configurations - single homogeneous soil layer.

Fig. 9 shows q/q_o results for the case of two unequal soil layers under the floor for different upper soil layer's thickness ratios (T_1/d), considering $K_1/K_2=4$. The thicknesses of the soil layers showed a noticeable effect on the seepage discharge ratio (q/q_o). Increasing T_1/d increases q/q_o for all the studied sheet piles angles and configurations. As T_1/d increases, the value of q/q_o approaches that of the case of a single homogeneous soil layer. The effect of T_1/d ratio is slight when it ranges from 0.25 to 0.75 because the sheet piles penetrate the low hydraulic conductivity soil layer (K_2). Further increasing of T_1/d in the range from 0.75 to 2 shows a greater increase in q/q_o because the depth of higher hydraulic conductivity soil under the sheet pile increases causing easier flow of the seeping water and reducing the efficiency of the sheet piles.

From **Fig. 9**, it's also clear that the case of double inclined sheet piles at the floor ends with an angle $\theta = 45^o$ and 135^o showed the best efficiency in reducing q/q_o which ranged from 0.15 to 0.37 for $\theta = 45^o$ and from 0.12 to 0.4 for $\theta = 135^o$. For a single sheet pile, the best configuration is found to be at the upstream end of the floor (X/L=0) with an inclination angle of $\theta = 135^o$ (q/q_o ranges from 0.15 to 0.43) and at the downstream end of the floor (X/L=1) with an inclination angle of 45^o (q/q_o ranges from 0.18 to 0.43). These results agree with the case of single homogeneous soil layer and are attributed to the same reasons discussed before. Locating the single sheet pile at the middle of the floor (X/L=0.5) showed the least performance in reducing q/q_o for all inclination angles and soil thicknesses.

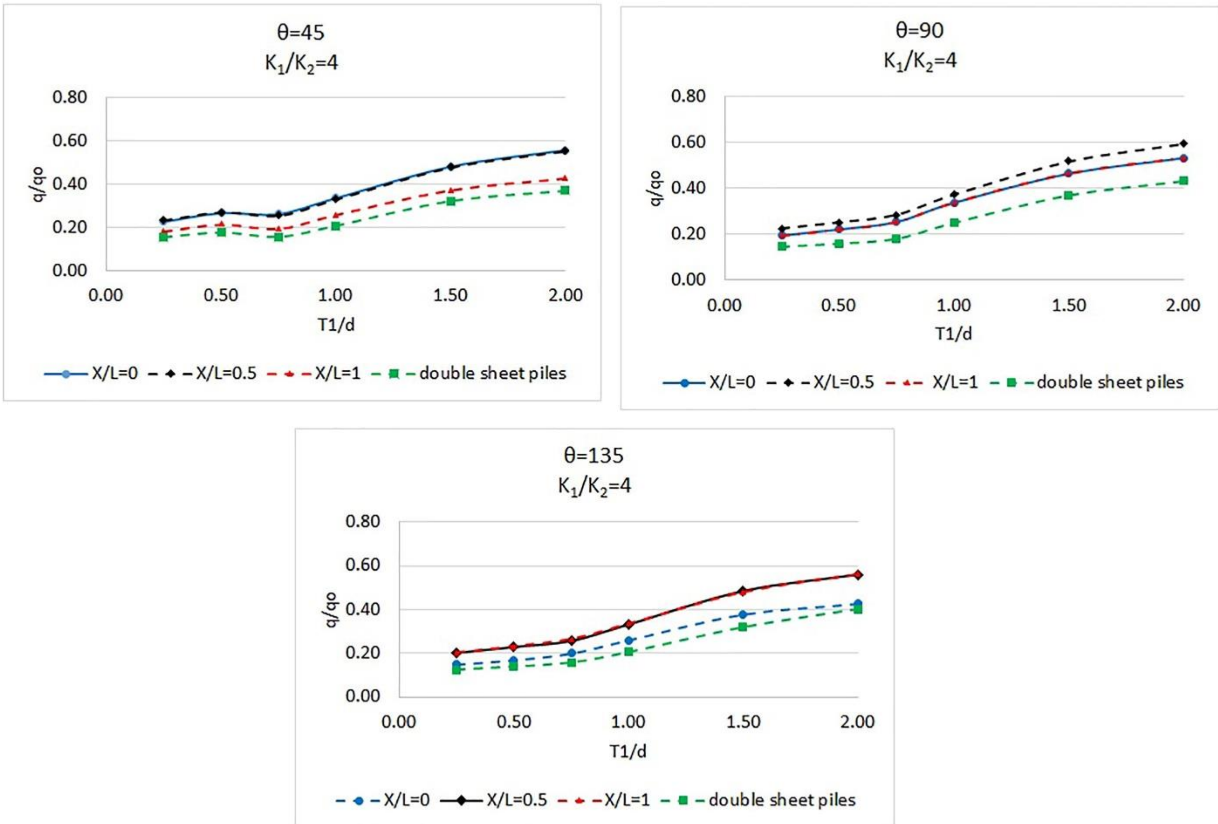

Fig. 9: Effect of T_1/d on q/q_o for different sheet piles angles and configurations ($K_1/K_2= 4$).

3.2.THE EFFECT OF SOIL LAYERS THICKNESSES ON THE UPLIFT FORCE.

Fig. 10 shows the results of uplift force ratio (F/F_o) for the case of single homogeneous soil layer. The case of single sheet pile located at the floor's upstream end (X/L=0) showed the best performance in reducing the uplift force ratio (F/F_o), especially for $\theta = 135^o$ which showed the least uplift force ratio (F/F_o=0.49) followed by the vertical sheet pile ($\theta = 90^o$) which resulted in F/F_o = 0.61, then $\theta = 45^o$ that resulted in F/F_o = 0.79. This can be due to the big head loss that occurs at the upstream end of the floor in this case, especially when $\theta = 135^o$, which reduces the water pressure under the floor leading to a less uplift force.

Fig. 10 also shows that using a single sheet pile at the downstream end of the floor (X/L=1) leads to the highest uplift force ratio for all the studied inclination angles, with a maximum value of F/F_o = 1.38 for $\theta = 45^o$. This is because using the sheet pile at this location adds an extra length to the floor's downstream end and causes more water pressure under it, with a maximum extra length when $\theta = 45^o$, resulting in a higher value for the uplift force. Hence, when using this sheet pile configuration (X/L=1) it is recommended to increase the thickness of the floor to ensure the structure's safety against uplift. For the case of double sheet piles, the uplift force is affected by the interference between the head lost at the beginning of the floor due to the upstream sheet pile and the extra length added to the floor due to the downstream sheet pile. In this case, the least uplift force occurred at $\theta = 135^o$ (F/F_o = 0.68).

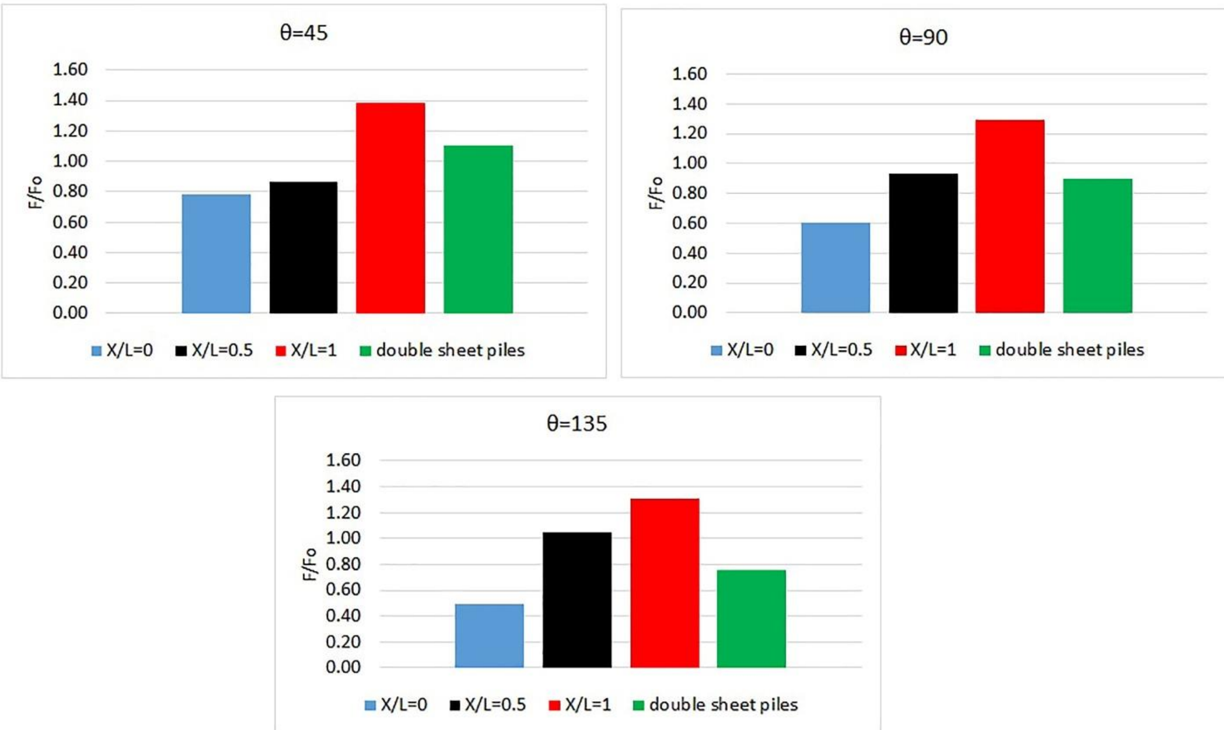

Fig. 10: F/F_o for different sheet piles angles and configurations - single homogeneous soil layer.

Fig. 11 shows the F/F_o results for the case of two unequal soil layers under the structure's floor with different T_1/d ratios, considering $K_1/K_2=4$. The least F/F_o occurred when a single sheet pile is used at the upstream end (at X/L=0), while the highest F/F_o occurred when a single sheet pile is used at the downstream end (at X/L=1), which agree with the results obtained for the single homogeneous soil layer. The interference between the effects of the upstream and downstream sheet piles in the case of double sheet piles is also clear, as their effect on the uplift force ratio changes for the different sheet pile inclination angles. The T_1/d ratio has slight to no effect on F/F_o for all the studied sheet pile configurations and inclination angles.

From **Fig. 11**, it is also noticed that for a single sheet pile at the upstream end (X/L =0), a smaller F/F_o resulted for T_1/d ranging from 0.25 to 0.75, then F/F_o slightly increased for T_1/d ranging from 0.75 to 2. This is because when T_1/d ranges from 0.25 to 0.75, the sheet pile penetrates the low hydraulic conductivity soil layer (K_2) and causes a bigger head loss at the upstream side of floor, leading to a further reduction in the water pressure under the floor, and hence, less uplift force in this case. For the cases of single sheet pile at X/L =0.5 and double sheet piles at the floor's ends, the ratio T_1/d has no effect on F/F_o. On the other side, for a single sheet pile at the downstream end (X/L=1), A slightly higher F/F_o was obtained for T_1/d ranging from 0.25 to 0.75, while F/F_o decreased for T_1/d ranging from 0.75 to 2. This is because when T_1/d ranges from 0.25 to 0.75, the penetration of the downstream sheet pile to the low hydraulic conductivity soil layer (K_2) causes more water pressure and uplift force under the floor.

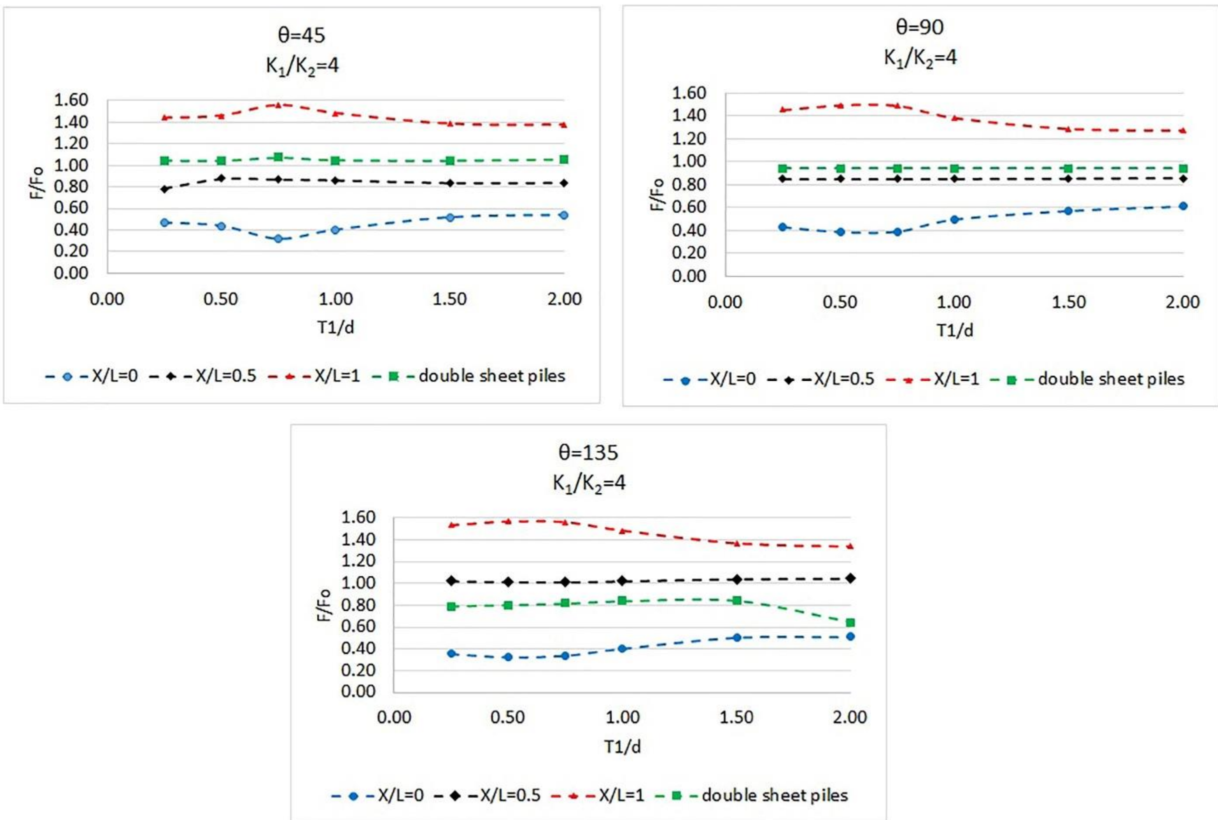

Fig. 11: Effect of T_1/d on F/F_o for different sheet piles angles and configurations (K_1/K_2= 4).

3.3.THE EFFECT OF SOIL LAYERS THICKNESSES ON THE EXIT GRADIENT.

Fig. 12 shows the results of the exit gradient ratio (E/E_o) for the case of single homogeneous soil layer. The case of double sheet piles at the floor's ends showed the best performance in reducing E/E_o, especially for $\theta = 45^o$ which provided the least exit gradient ratio (E/E_o=0.11), followed by the vertical sheet pile ($\theta = 90^o$) which resulted in E/E_o = 0.22, then $\theta = 135^o$ (E/E_o = 0.28). On the other side, using a single sheet pile at the downstream end (X/L=1) with $\theta = 45^o$ gave the least exit gradient ratio (E/E_o =0.11). Next comes the vertical downstream sheet pile (X/L=1, $\theta = 90^o$) which resulted in E/E_o=0.28, then the case of upstream inclined sheet pile with $\theta = 135^o$ which resulted in E/E_o = 0.36. This can be due to the longer path that the seeping water follows in such sheet pile configurations, which reduces the exit gradient.

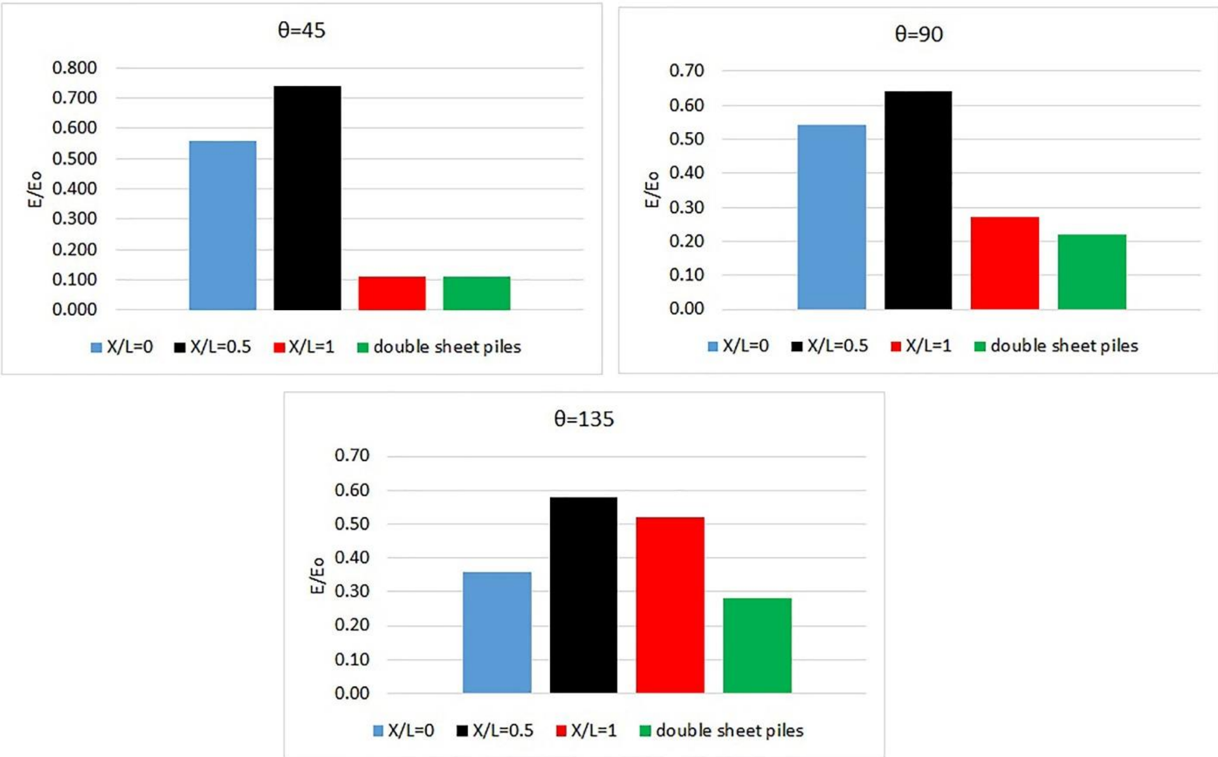

Fig. 12: E/E_o for different sheet piles angles and configurations - single homogeneous soil layer.

Fig. 13 shows E/E_o results for two unequal soil layers under the structure's floor with different T_1/d ratios, taking K_1/K_2=4. The thicknesses of the soil layers showed a noticeable effect on E/E_o in the cases of single sheet pile at X/L=0 and X/L=0.5. On the contrary, a less effect was observed for single sheet pile at X/L=1 and double sheet piles (except for $\theta = 135^o$). The effect of T_1/d ratio is slight for all the sheet piles configurations when T_1/d ranges from 0.25 to 0.75 because the sheet piles penetrate the low hydraulic conductivity soil layer (K_2) causing more resistance to the flow. Increasing T_1/d ratio from 0.75 to 2 noticeably increases E/E_o for all the studied sheet piles angles and configurations. This is because as the thickness of the high hydraulic conductivity layer (K_1) increases, the sheet piles stop penetrating the low hydraulic conductivity layer (K_2), causing less resistance to the flow, and consequently an easier flow of the seeping water and less head loss.

It is also clear from **Fig. 13** that the case of double inclined sheet piles at the floor ends has the best efficiency in reducing the exit gradient ratio (E/E_o). The ratio E/E_o ranged from 0.08 to 0.11 for $\theta = 45^o$, followed by 0.09 to 0.19 for $\theta = 90^o$, and 0.08 to 0.19 for $\theta = 135^o$. For a single sheet pile, the best configuration is found to be at the downstream end of the floor (X/L=1) with $\theta = 45^o$ (E/E_o ranges from 0.07 to 0.12) followed by the same location with $\theta = 90^o$ (E/E_o ranges from 0.12 to 0.22), then at the upstream end of the floor (X/L=0) with $\theta = 135^o$ (E/E_o ranges from 0.09 to 0.33). These results agree with the case of single homogeneous soil layer for the same reasons that were previously discussed.

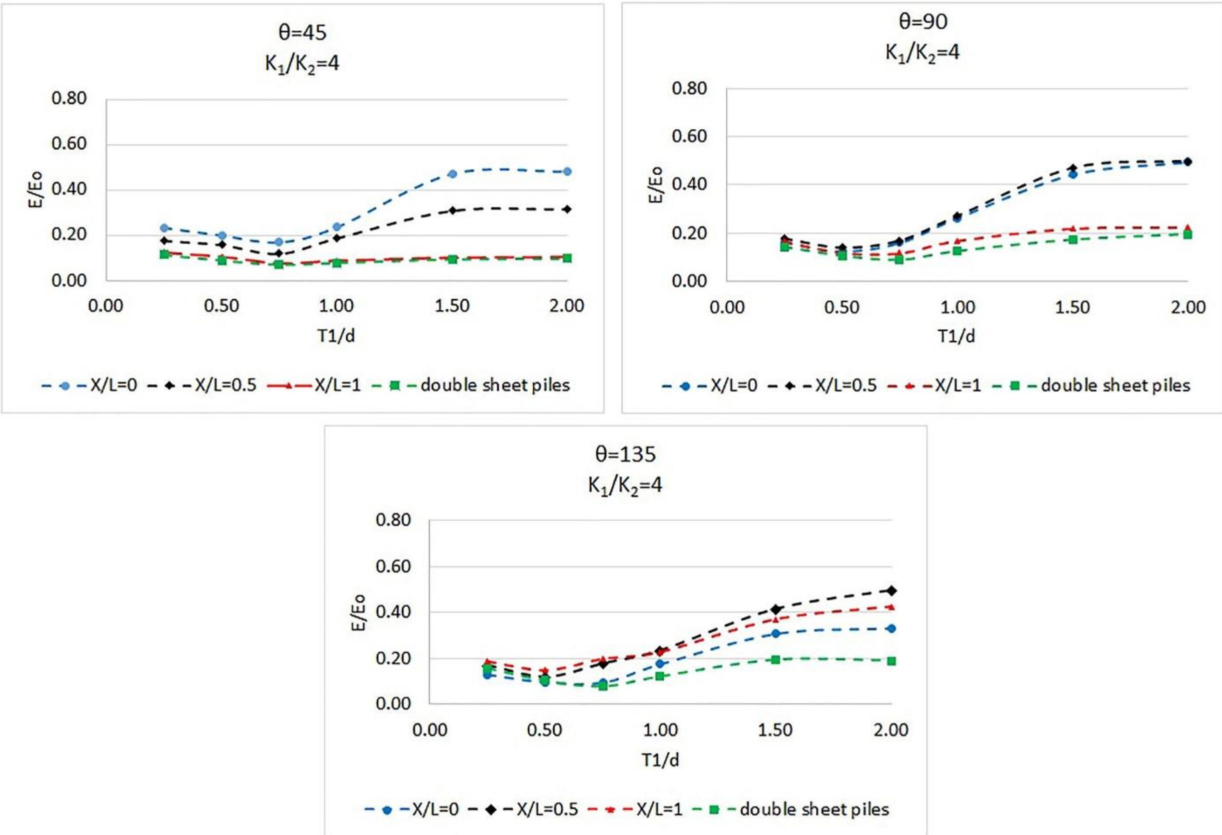

Fig. 13: Effect of T_1/d on E/E_o for different sheet piles angles and configurations (K_1/K_2= 4).

3.4.THE EFFECT OF SOIL LAYERS HYDRAULIC CONDUCTIVITY RATIO ON THE SEEPAGE DISCHARGE.

Fig. 14 shows the effect of soil layers hydraulic conductivity ratio (K_1/K_2) on the seepage discharge ratio (q/q_o) for different T_1/d ratios. In order to capture the effect of soil characteristics only, a single vertical sheet pile ($\theta = 90^o$) is used at the floor's upstream end (X/L=0). The results show that when the upper layer has a higher hydraulic conductivity ($K_1/K_2 >1$), increasing the hydraulic conductivity ratio (K_1/K_2) causes q/q_o to decrease for all T_1/d ratios, this can be because as the lower layer's hydraulic conductivity (K_2) decreases, it causes more resistance to the flow and forces most of the seeping water to move in the upper layer only, reducing the flow's cross sectional area, and consequently, the amount of seepage discharge. Increasing T_1/d ratio in such case ($K_1/K_2 >1$) increases q/q_o because it increases the cross sectional area of the higher hydraulic conductivity soil. On the other side, when the upper layer has a lower hydraulic conductivity (K_1/K_2 <1), increasing K_1/K_2 increases q/q_o. This is because as K_1/K_2 approaches the value of 1, the upper layer poses less resistance to the flow and allows more water to flow through it. In this case (K_1/K_2 <1), increasing T_1/d causes the reduction of seepage discharge ratio (q/q_o), because the depth of lower hydraulic conductivity layer (K_1) increases causing more resistance to the flow.

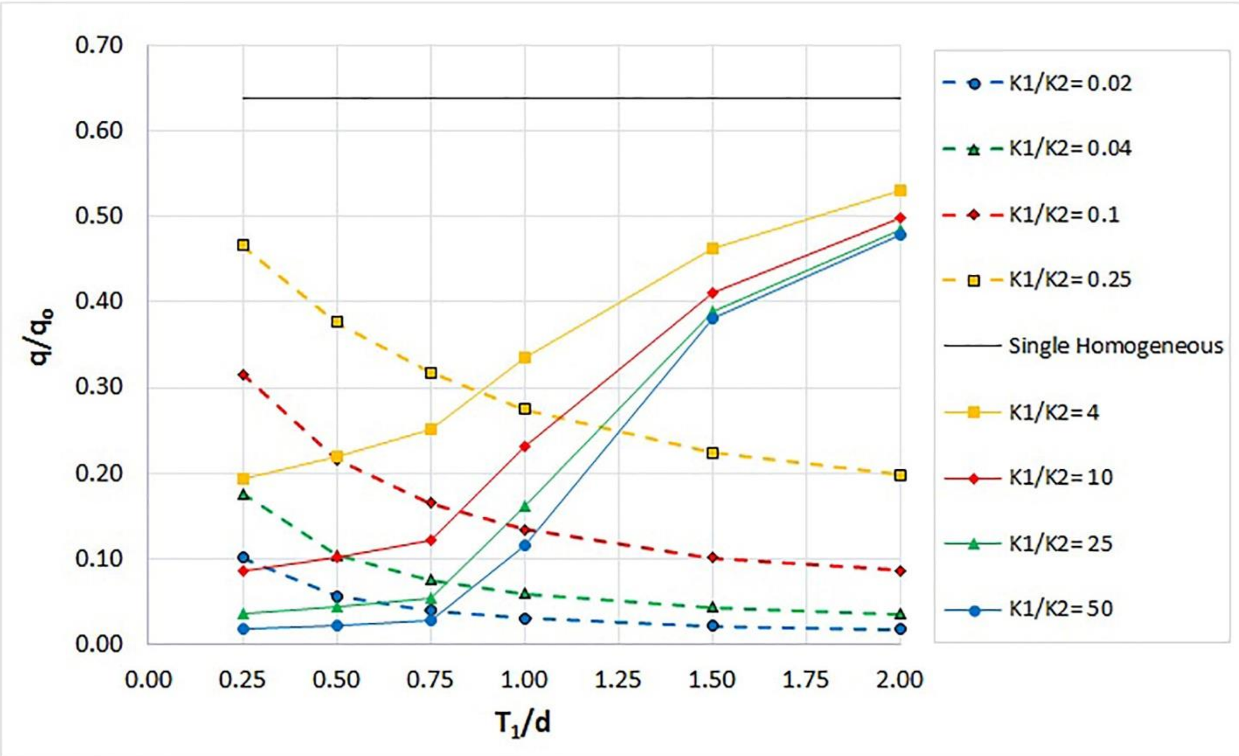

Fig. 14: Effect of soil layers hydraulic conductivity ratio (K_1/K_2) on q/q_o.

3.5.THE EFFECT OF SOIL LAYERS HYDRAULIC CONDUCTIVITY RATIO ON THE UPLIFT FORCE.

Fig. 15 shows the effect of K_1/K_2 ratio on the uplift force ratio (F/F_o) for different T_1/d ratios, for a single upstream vertical sheet pile ($X/L=0$, $\theta = 90^o$). The results show that increasing K_1/K_2 ratio reduces F/F_o. This effect is more noticeable for smaller T_1/d ratios. For $T_1/d > 1$, the hydraulic conductivity ratio (K_1/K_2) has no effect on the results. This can be because when K_1/K_2 >1 and $T_1/d \leq 1$, the sheet pile penetrates the low conductivity layer (K_2) and causes a bigger head loss at the beginning of the floor, hence, the amount of head lost is affected by the lower layer's hydraulic conductivity. Also, when the upper soil layer has a lower hydraulic conductivity (K_1/K_2 <1) and $T_1/d \leq 1$, increasing T_1/d causes more resistance to the flow, which leads to a higher head loss at the upstream, and consequently, less uplift force.

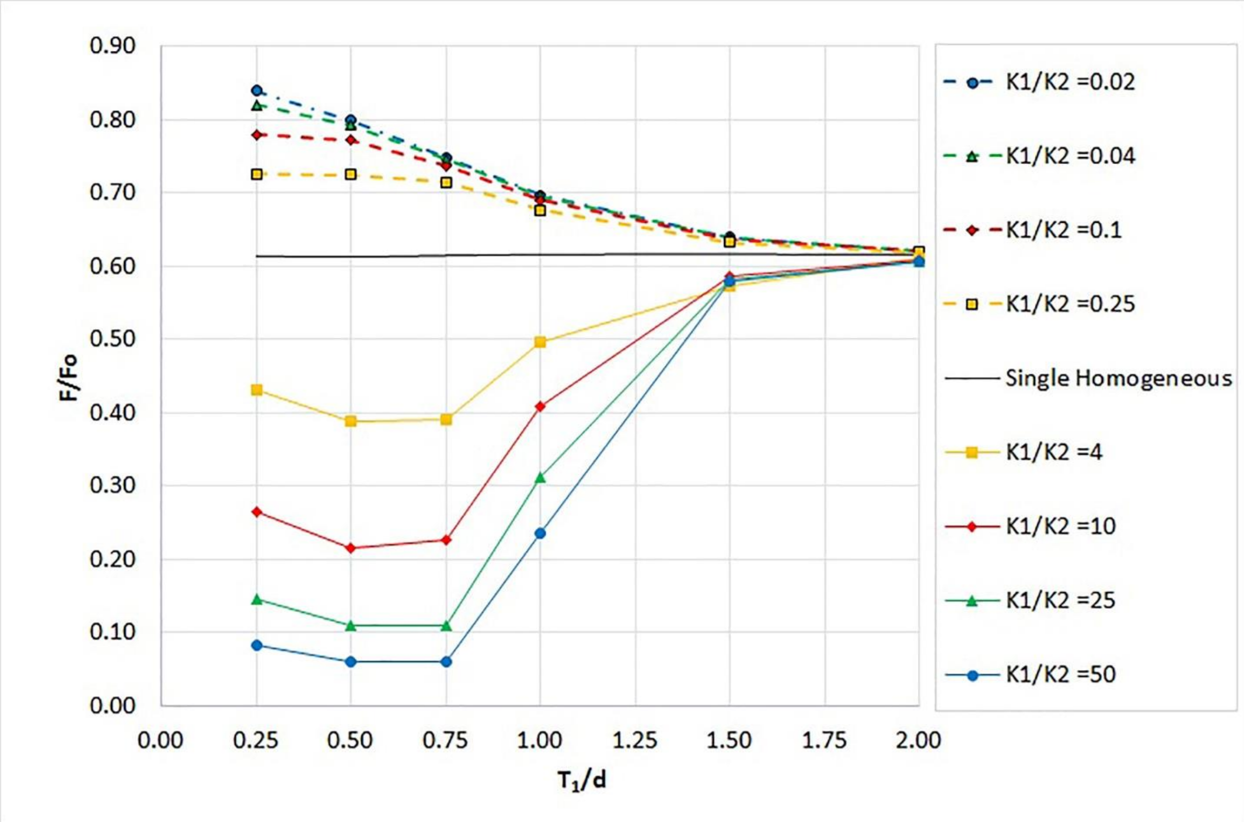

Fig. 15: Effect of soil layers hydraulic conductivity ratio (K_1/K_2) on F/F_o.

3.6.THE EFFECT OF SOIL LAYERS HYDRAULIC CONDUCTIVITY RATIO ON THE EXIT GRADIENT.

Fig. 16 shows the effect of K_1/K_2 ratio on the exit gradient ratio (E/E_o) for different T_1/d ratios considering a single upstream vertical sheet pile ($X/L=0$, $\theta = 90^o$) under the floor. From the results, it is clear that increasing K_1/K_2 ratio leads to the reduction of the (E/E_o). When the upper layer has a higher hydraulic conductivity ($K_1/K_2 >1$), increasing T_1/d ratio causes the increase of E/E_o due to the less penetration of the sheet pile into the low conductivity layer which leads to a smaller head loss and a higher exit gradient. On the contrary, When the upper layer has a lower hydraulic conductivity ($K_1/K_2 <1$), increasing T_1/d ratio causes the reduction of E/E_o because as the thickness of low hydraulic conductivity layer increases, it leads to a higher head loss through it and a smaller exit gradient.

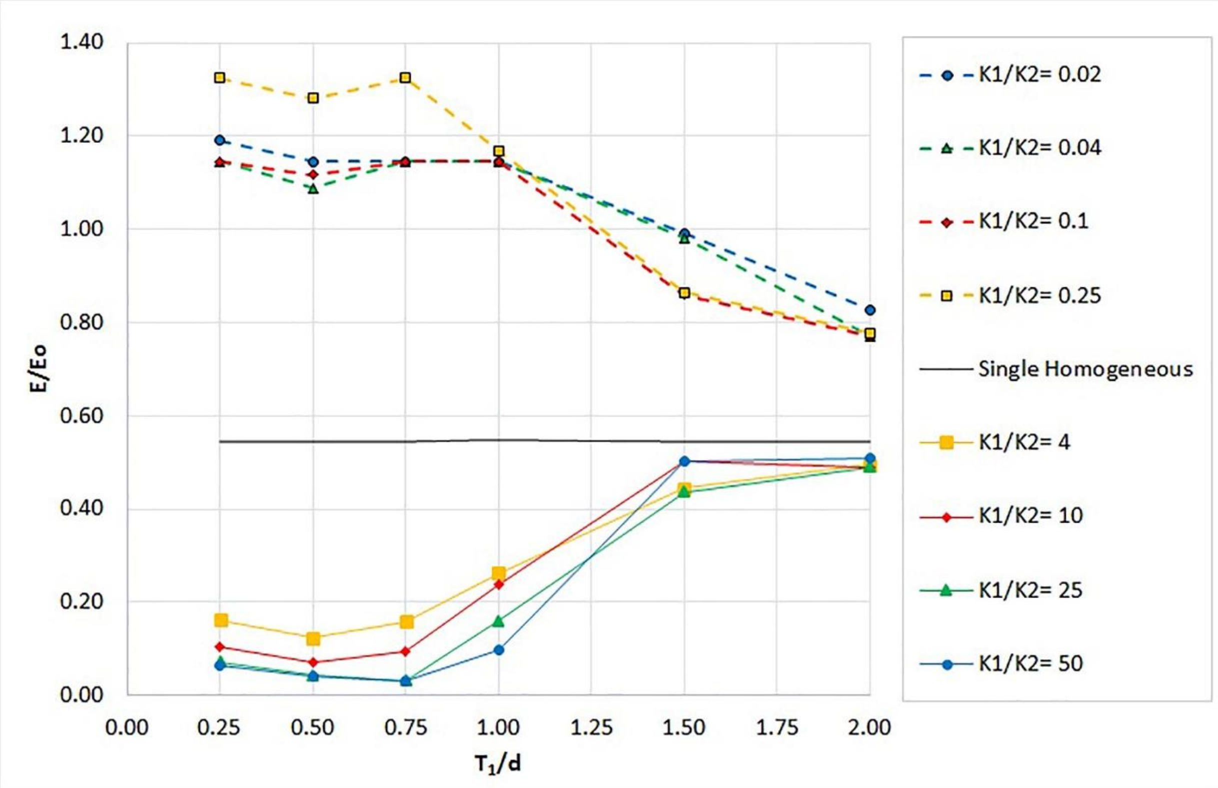

Fig. 16: Effect of soil layers hydraulic conductivity ratio (K_1/K_2) on E/E_o.

4. CONCLUSIONS

In this study, the effect of soil layers thicknesses and hydraulic conductivity ratios on the efficiency of different configurations of vertical and inclined sheet piles is evaluated. Two different soil layers of unequal thicknesses are considered under the structure's floor. The sheet piles' location, number, and inclination angle showed a significant effect on the seepage discharge, uplift force, and exit gradient. The upper soil layer's thickness ratio (T_1/d) and the hydraulic conductivity ratio (K_1/K_2) also have a great effect on the efficiency of sheet piles and should be considered in their design. The sheet piles penetration into the low hydraulic conductivity layer is also very effective.

The case of double sheet piles at the floor's ends has the best performance in reducing the seepage discharge ratio (q/q_o) and exit gradient ratio (E/E_o) for all the studied scenarios, especially for inclined sheet piles with $\theta = 45^o$. The single upstream inclined sheet pile (X/L=0) with an angle of $\theta = 135^o$ and single downstream inclined sheet pile (X/L=1) with an angle of $\theta = 45^o$ come in second place.

The case of single upstream sheet pile (X/L=0) showed the best performance in reducing the uplift force ratio (F/F_o), especially for $\theta = 135^o$. On the other side, using a single downstream sheet pile (X/L=1) leads to the highest uplift force for all the studied inclination angles, with $\theta = 45^o$ having the maximum value, hence, it is recommended in such case to increase the thickness of the floor to ensure the structure's safety against uplift. The single sheet pile configuration at the middle of the floor (X/L=0.5) is not recommended to be used to reduce the seepage discharge, uplift force, or exit gradient.

T_1/d has a slight effect on the uplift force ratio (F/F_o) for all the studied sheet pile configurations and inclination angles while, its effect on the seepage discharge ratio (q/q_o) and exit gradient ratio (E/E_o) is significant. The effect of T_1/d ratio on E/E_o is slight when the sheet pile penetrates the lower conductivity soil layer (T_1/d = 0.25 to 0.75). Increasing T_1/d ratio from 0.75 to 2 noticeably increases the exit gradient ratio (E/E_o) for all the studied sheet piles angles and configurations.

When the upper soil layer has a higher hydraulic conductivity ($K_1/K_2 >1$), increasing K_1/K_2 causes q/q_o and E/E_o to decrease for all T_1/d ratios, while increasing T_1/d increases q/q_o and E/E_o. On the contrary, when the upper soil layer has less hydraulic conductivity ($K_1/K_2 <1$), increasing K_1/K_2 increases q/q_o and reduces E/E_o, and increasing T_1/d causes the reduction of q/q_o and E/E_o.

For the uplift force, Increasing K_1/K_2 ratio reduces F/F_o in a more noticeable way for T_1/d ranging from 0.25 to 1, while for $T_1/d > 1$ it has no effect on the uplift results. As long as the sheet piles penetrate the low hydraulic conductivity soil layer (K_2), T_1/d =0.25 to 0.75, the effect of T_1/d on the seepage discharge ratio, uplift force ratio, and exit gradient ratio is considered slight.

5. REFERENCES

[1] Harr ME. Groundwater and Seepage, McGraw- Hill, New York, 1962. 1962.

[2] El-Molla AM. New Trend For Evaluating The Percolation Length Under Aprons Of Hydraulic Structures Provided With Cutoff And Founded On Isotropic Soil. Civ Eng Res Mag 2001;23.

[3] Mobasher A. Efficiency of cutoffs under aprons of irrigation structures. M.Sc. Thesis, Al Azhar University, Cairo, 2005.

[4] Jamel AAJ. Effect of Two Sheet Piles In Double Soil Layers on Seepage Properties Under Hydraulic Structure Using SEEP/W Program. Al-Nahrain J Eng Sci 2017;20:194–205.

[5] Rasool M. Effect of Mutual Interference Piles on Seepage Properties Under Hydraulic Structures. Kufa J Eng 2018;9:273–85. https://doi.org/10.30572/2018/kje/090419.

[6] El Molla MA, Saad NY, Ezizah GS. Evaluation of actual creep length under heading up structures aprons. Ain Shams Eng J 2018. https://doi.org/10.1016/j.asej.2018.03.009.

[7] Abdelaal M, Ahmed H, El Molla D, Anas M. Numerical Investigation of Creep Length under Effect of Cutoffs in Hydraulic Structures. Al-Azhar Univ Civ Eng Res Mag 2018;40:231–40.

[8] El-Molla MA, Abdelaal MA, Khalifa AE-KA. Evaluation of Seepage Length between Cutoffs under Heading up Structures founded on a Stratified Soil. Life Sci J 2018;15:40–7. https://doi.org/10.7537/marslsj150618.05.Keywords.

[9] Al Tabatabaie F, Al Waily DS. The Effect of Cutoffs on the Uplift Pressure Beneath the Hydraulic Structures Floor. Wasit J Eng Sci 2018;6:20–8. https://doi.org/10.31185/ejuow.vol6.iss3.101.

[10] Shousha MA, Basha AM, El-enany MA, Moghazy HM. Effect of using grouted vertical barrier on seepage characteristics under small hydraulic structures. Alexandria Eng J 2020. https://doi.org/10.1016/j.aej.2020.01.013.

[11] Salmasi F, Nourani B, Abraham J. Investigation of the effect of the different

configurations of double-cutoff walls beneath hydraulic structures on uplift forces and exit hydraulic gradients. J Hydrol 2020;586:124858. https://doi.org/10.1016/j.jhydrol.2020.124858.

[12] Ahmed AA, Bazaraa AS. Three-Dimensional Analysis of Seepage below and around Hydraulic Structures. J Hydrol Eng 2009;14:243–7. https://doi.org/10.1061/(asce)1084-0699(2009)14:3(243).

[13] Ahmed AA. Design of hydraulic structures considering different sheetpile configurations and flow through canal banks. Comput Geotech 2011;38:559–65. https://doi.org/10.1016/j.compgeo.2011.03.004.

[14] Afzali ES, Barani GA. Application of SEEP 3D software in modelling the effects of cutoff walls on the reduction of the seepage pressure and exit hydraulic gradient under hydraulic structure. Sci Inf Database 2013;5:79–90.

[15] Gad MA, Anas D, Atta NA, Samy G. Worth of the three dimensional simulations of seepage in the vicinity of heading-up structures. KSCE J Civ Eng 2016;20:679–86. https://doi.org/10.1007/s12205-015-1579-2.

[16] Alsenousi KF, Mohamed HG. Effects of inclined cutoffs and soil foundation characteristics on seepage beneath hydraulic structures. Twelfth Int. Water Technol. Conf., Alexandria, Egypt: 2008.

[17] Obead IH. Effect of Position and Inclination Angle of Cutoff Wall on Seepage Control in the Foundation of Dam Structure. J Kerbala Univ 2013;11:17–32.

[18] Mansuri B, Salmasi F, Oghati B. Effect of Location and Angle of Cutoff Wall on Uplift Pressure in Diversion Dam. Geotech Geol Eng 2014;32:1165–1173. https://doi.org/10.1007/s10706-014-9774-3.

[19] Moharrami A, Moradi G, Bonab MH, Katebi J, Moharrami G. Performance of Cutoff Walls Under Hydraulic Structures Against Uplift Pressure and Piping Phenomenon. Geotech Geol Eng 2015;33:95–103. https://doi.org/10.1007/s10706-014-9827-7.

[20] Khalili Shayan H, Amiri-Tokaldany E. Effects of blanket, drains, and cutoff wall on reducing uplift pressure, seepage, and exit gradient under hydraulic structures. Int J Civ Eng 2015. https://doi.org/10.22068/IJCE.13.4.486.

[21] Alnealy HKT. Determination the Flow Net through Multi Layers Soil by Using the Hydraulic Modeling Method. Am J Civ Eng 2015;3:80–7. https://doi.org/10.11648/j.ajce.20150303.15.

[22] Alghazali NOS, Alnealy HKT. Experimental Analysis of Seepage in Soil Beneath a Model of a Gravity Dam. Am J Civ Eng 2015;3:64–9. https://doi.org/10.11648/j.ajce.20150303.12.

[23] Alnealy HKT, Alghazali NOS. Analysis of Seepage Under Hydraulic Structures Using Slide Program. Am J Civ Eng 2015;3:116–24. https://doi.org/10.11648/j.ajce.20150304.14.

[24] Hussein KB, Dardier MA, Seif AK, Elsheemy AA. Studying Effect Inclination of cutoff on the percolation Length under Aprons of Hydraulic Structures Founded on Isotropic soil. Int Res J Eng Technol 2017;4:1208–24.

[25] Bakr A, El-Masry A, Masria A, Abdelgawad HAA. Effect of Cut off Position and Inclination on Seepage Characteristics under Heading-up Structure Using Differential Quadrature Element Method. Int J Sci Eng Res 2019;10:541–8.

[26] Elmolla AM, Abd Elgalil WA, Dardeer MA. Evaluate the Best Inclination Angle of Cutoff beneath Hydraulic Structures. Int Res J Eng Technol 2020;7:3966–74.

[27] Salim IH, Othman BS. The Effect of inclined intermediate Sheet Pile on Seepage Properties Under Hydraulic Structure Using SEEP/W Program. 2nd Int. Sci. Conf. Eng. Sci. (ISCES 2020) IOP Conf. Ser. Mater. Sci. Eng., Iraq: 2021, p. 1–9. https://doi.org/10.1088/1757-899x/1076/1/012131.

[28] Armanuos AM, Negm AM, Javadi AA, Abraham J, Gado TA. Impact of inclined double-cutoff walls under hydraulic structures on uplift forces , seepage discharge and exit hydraulic gradient. Ain Shams Eng J 2021. https://doi.org/10.1016/j.asej.2021.06.017.

[29] SEEP2D Primer Version 10. Groundwater Modeling System: Brigham Young University - Engineering Computer Graphics Laboratory, (1998). 1998.

[30] Glantz SA, Slinker BK. Primer of Applied Regression and Analysis of Variance. New York: McGraw-Hill; 1990.

6. NOMENCLATURE

d= depth of the sheet pile (L).
E= exit gradient (dimensionless).
E_o= exit gradient in the reference case (dimensionless).
F= uplift force on the floor's bottom per unit width of the floor (MT^{-2}).
F_o= uplift force on the floor's bottom in the reference case per unit width of the floor (MT^{-2}).
g= gravitational acceleration (LT^{-2}).
H= upstream water head (L).
K_1= hydraulic conductivity of upper soil layer (LT^{-1}).
K_2= hydraulic conductivity of lower soil layer (LT^{-1}).
L= length of the floor (L).
q= total flow rate per unit width of the floor (L^2T^{-1}).
q_o= total flow rate in the reference case per unit width of the floor (L^2T^{-1}).
R^2 = coefficient of determination (dimensionless).
T_1= thickness of the upper layer of soil (L).
T= total thickness of the soil under the floor (L).
X= location of the sheet pile measured from the beginning of the floor (L).
Ө= inclination angle of sheet pile (dimensionless).
ρ_w = density of water (ML^{-3}).