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Seepage Characteristics under Hydraulic Structure Foundation (Supported by Sheet pile) In Multi-Layers Soil

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ABSTRACT

This paper aims to study the effect of sheet pile on seepage characteristics under the hydraulic structure floor through soil consists of two layers that for convergence to exact case similar to studying case in nature. The effect of changing each of the effective water head, the sheet pile location under the floor of hydraulic structure, the sheet pile penetration depth in the soil layers and the arrangement of soil layers was done. In this paper the seepage characteristics was studied experimentally (Sand Model) and Numerically (Geo-Studio SEEP/W Model). The experimental and numerical results confirmed that the uplift pressure values decrease along the floor in case of upstream sheet pile depth was less than half depth of coarse sand and when the upper layer was coarse sand. The comparisons between sand model results and numerical results give a good agreement.

1. INTRODUCTION

The seepage phenomenon is of great importance to be investigated. The effect of seepage on the hydraulic structures is particularly studied for its destructive behaviour. The deteriorative effect of seepage on the hydraulic system might be sudden or by time. The resulting damages can be sorted into partial or overall damages (Belanger, 1990)[1].

In the present study, the problem of the seepage under the floor of hydraulic structure was investigated experimentally using the sand model and numerically using finite element method. The objective of this study is to investigate the influence of the effective water head acting on the hydraulic structure, depth and location of the sheet pile, arrangement of the sub-layers under the hydraulic structure floor on the following flow characteristics (Seepage unit discharge, q, Uplift pressure, U and Hydraulic gradient, I).

The major important result of this study was the seepage discharge and the hydraulic gradient values increase with increasing the permeability of the upper layer in case of the sheet pile only penetrates the upper layer and decrease with increasing the permeability of the upper layer in case of the sheet pile depth higher than the upper layer depth.

2. LITERATURE REVIEW

Seepage phenomena was studied empirically by Bligh (1912)[2] and Lane (1935)[3].

Bligh(1912)[2], based on his experience with Indian hydraulic constructions, he made an empirical theory, named Bligh's Creep Theory, this formula is also accompanied by factors named after Bligh " Bligh's coefficient, C_B", according the soil resistance to water flow.

$L_P = C_B H_{max}$

Lane (1935)[3], developed the weighted creep method to find the true ratio of the respective "weights" of vertical and horizontal contacts. Lane estimated the

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efficiency ratio of horizontal to vertical lengths to be one-to-three of the floor length considering all sloping contacts less than 45° to be added to horizontal sum. The safe total length of the floor, LW, is according to Lane as:

$L_w = C_L H_{max}$

Das (1983)[4], developed "flow nets" which is the graphical solution of Laplace's equation. This solution is presented by two sets of curves intersecting at right angles. The curves of one set are called flow lines and those of the other are called equipotential lines. The equipotential line is a line passing through points of equal hydraulic potential or head. If piezometers are inserted along equipotential line, water will rise to the same elevation in all piezometers.

Chawla (1972)[5], studied the boundary effects in models on the seepage characteristics (uplift pressure, exit gradient). The chwarz-christofell transformation was used to determine the end effects. Chawla's concluded that, The uplift pressure below a floor with a central cutoff and equal pervious reaches on the upstream and downstream sides increases on the upstream and decreases on the downstream side of the cutoff, for an equal increase in the length of pervious reaches on either side.

EL-Ganainy (1986)[6], using the "Conformal Mapping" technique introduced an exact solution for the seepage beneath a solid flat floor of a hydraulic structure founded on a pervious stratum.

Pavlovsky (1935)[7], established an approximate method to solve the confined flow through a pervious layer of finite depth, known as the method of fragments, the equipotential lines at various critical locations in the flow region can be approximated by straight vertical lines.

Zaki (1964)[8], used "Electrical Analogy model" to study the seepage characteristics under hydraulic structures and concluded that, the design of hydraulic structures by using the "Electrical Analogy" method achieved high degree of accuracy.

Hassan, (1989)[9], studied the problem of seepage under floor of the hydraulic structures experimentally using the "Hele-Shaw model", he verified that, The best position of one row of sheet piles walls is at the first third of the floor length because of the lowest values of pressure occur just after that position.

Nassrallah T.H. (2001)[10], investigated the effect of sub layers formation as thickness and order on seepage characteristics (uplift pressure, seepage discharge, and hydraulic gradient) through studying two horizontal layers with different arrangement and relative thickness, he used "sand model" and shown that, When the water head, H, increase, the values of the relative uplift pressure, U/H_o, the seepage discharge, Q, and the hydraulic gradient, I, increase too.

El-Masry (1993)[11], studied ten cases of the downstream pervious portions under the structure using the “Boundary Element Method”, to investigate the effect of insufficient pervious length downstream of hydraulic structures. He concluded that, decreasing the thickness of the permeable layer underneath the structure decreases the seepage discharge, uplift pressure and the exit gradient.

Najjar and et al, (1999)[12], developed a finite element model using eight-nodes element to provide seepage and exit-gradient estimates under single sheet piles penetrating two-layered media. The data obtained from the numerical model were compiled and plotted to form different sets of design charts. These charts could be used efficiently for obtaining seepage and exit-gradient estimates under the aforementioned hydraulic structure.

Saleh I. Khassaf, et al., (2009)[13], studied the water seepage below Diyala weir structure. The quantity of seepage, pressure head and exit gradient were calculated using (GEOSLOPE, SEEP/W) model. Saleh concluded that, the defects in the first row of sheet piles are more effective on increasing uplift pressure and quantity of seepage than the other two rows of sheet piles while defects in the last rows of sheet piles are more effective on increasing the exit hydraulic gradient.

3. Dimensional analysis

The dimensional analysis process divided into many steps reported as:

- Definition of the main considered parameters (input or output).
- Description for the dimensions of parameters.
- Analyze the parameters dimensions with a mathematical Dimensional analysis method (Buckingham - π Theorem).

Three main groups are defined as considered variables and parameters.

The first group is the Model characteristics, which contain the Hydraulic structure floor length, L, the Hydraulic structure floor width, B, Distance measured from the toe of the floor, X, the Sheet pile location under the floor from the toe, X_s, the Distance of application point of the uplift pressure force measured from the toe of the floor, X_u, the Sheet pile penetration depth, S, and The effective water head, H_o.

The second group is the soil characteristics, which contain the Total depth of soil layers under the hydraulic structure floor, D, Depth of the upper and lower soil layer, D_u, D_L, the Permeability coefficient of the upper and lower layer of soil, K_u, K_L, the Equivalent permeability coefficient of soil layers under the floor, K_{eq}, Water density (γ_w) and Soil density of upper and lower layer (γ_{su} ,γ_{sl}).

The last group is the Seepage characteristics, which contain the uplift pressure, U, the seepage unit discharge, q, and the hydraulic gradient, I. Fig. (1).

Finally, the relations between variables and main parameters can be summarized as:

$$\frac{U}{\gamma w \times Hmax} = C_3 f\left(\frac{X}{L}, \frac{Xs}{L}, \frac{S}{D}, \frac{Ho}{Hmax}, \frac{Ku}{Kl}\right)$$

$$\frac{q}{Keq \times Hmax} = C_3 f\left(\frac{Xs}{L}, \frac{S}{D}, \frac{Ho}{Hmax}, \frac{Ku}{Kl}\right)$$

$$I = \frac{hl}{X} = C_3 f\left(\frac{X}{L}, \frac{Xs}{L}, \frac{S}{D}, \frac{Ho}{Hmax}, \frac{Ku}{Kl}\right)$$

$$\frac{Xu}{L} = C_3 f\left(\frac{Xs}{L}, \frac{S}{D}, \frac{Ho}{Hmax}, \frac{Ku}{Kl}\right)$$

4. Numerical Model Setup

After showing the Theoretical Engineering basis and Features and benefitsfor the SEEP/W program, the work procedures for the numerical model on the SEEP/W programs were done as follows:

4.1- Construct the model

- Define the working area size , choosing the engineering units and set the used scale.
- Sketch axes to define an evenly-spaced region for the axes, the number of increments along each axes is calculated by SEEP/W when the axes were generated.
- Prepare the sketch model dimensions for Drawing the problem region.

4.2- Analysis parameters

- The first analysis parameters was the analysis type, the analysis type was selected as steady-state solution.
- The analysis control was chosen as two-dimensional analysis.
- Define hydraulic conductivity coefficients of used soil layers, and define the soil materials properties, table (1).
- Generate regions and finite elements, draw the region boundary and choose number of elements in X and Y directions for region. The region was divided automaticaly by SEEP/W to number of elements.

4.3- Boundary conditions

- Boundary conditions in the study problem means the total head acting on upstream and downstream soil free surfaces.
- The total head acting in the study problem, table (2).
- The total head acting on the downstream side was constant value and equal 2.0 cm.

4.4- Drawing flux section

A flux section was required for the aim of the studying problem to compute the total seepage flow through the floor of hydraulic structure model, flux section was drawn completely across the elements which located under the hydraulic model floor in order to include the flux through the elements.

4.5- Verification of the studying problem data

Before solution start, the problem data shoud be verified by SEEP/W to insure that the data has been defined correctly, SEEP/W was performed a number of checks on the nodes and elements data, including filling any missing data, any missing node number, element overlap, intial water table, and appear this checks in the dialog box.

4.7- Output and results

After the previous steps were done the output results can earn by seep/w as follow:

- Generating contour plot.
- Displaying velocity vectors that represent the flow direction.
- Displaying the computed flux across the specified section.
- Displaying the numerical informations for individual nodes and elements.
- Plotting graphs of the computed results.

5. LABORATORY EXPRIMRNTS

The experiments divided into two main groups depending on the arrangement of soil layers under the foundation of hydraulic structure, with verifying constancy of equivalent permeability coefficient from harmony of layers.

Many parameters considered constant in the experiments, these parameters are:

1- Total depth of layers (D),
2- Depth of upper layer (D_u),
3- Depth of lower layer (D_L),
4- Length of model floor(L),
5- Width of model floor (W) and
6- Water density (γ_w).

The experiments were investigating the effect of various parameters on the seepage characteristics (uplift pressure, seepage discharge, exit gradient). These parameters were:

1- The effective water head, H_o, acting on the hydraulic structure (deference between upstream and downstream water head).
2- The arrangement of soil layers under the foundation of hydraulic structure.
3- The sheet pile penetration depth in soil layers, S.
4- The position of sheet pile beneath the foundation of hydraulic structure, X.

Table (1): Soil properties under the foundation of hydraulic structure.

Soil properties		Coarse sand	Medium sand
Sieve analysis	Pass from	Sieve 1.00 mm	Sieve 600 µmm
	Retained on	Sieve 710 µmm	Sieve 420 µmm
Dry unit weight		1.508 Kg/m^3	1.472 Kg/m^3
Permeability coeff. (K)		0.17869 cm/sec	0.036388 cm/sec

Table (2): Experimental scheme.

No.	Soil layers arrangement	Sheet pile location	Sheet pile Depth cm	Water effective head cm	No. of exp.
1	Upper layer: coarse sand Lower layer: medium sand	Toe	0.0	4.0, 8.0, 12.0, 16.0	4
2			12	4.0, 8.0, 12.0, 16.0	4
3			24	4.0, 8.0, 12.0, 16.0	4
4			36	4.0, 8.0, 12.0, 16.0	4
5			48	4.0, 8.0, 12.0, 16.0	4
6		Middle	24	4.0, 8.0, 12.0, 16.0	4
7			48	4.0, 8.0, 12.0, 16.0	4
8		Heel	24	4.0, 8.0, 12.0, 16.0	4
9			48	4.0, 8.0, 12.0, 16.0	4
10	Upper layer: medium sand Lower layer: coarse sand	Toe	0.0	4.0, 8.0, 12.0, 16.0	4
11			12	4.0, 8.0, 12.0, 16.0	4
12			24	4.0, 8.0, 12.0, 16.0	4
13			36	4.0, 8.0, 12.0, 16.0	4
14			48	4.0, 8.0, 12.0, 16.0	4
15		Middle	24	4.0, 8.0, 12.0, 16.0	4
16			48	4.0, 8.0, 12.0, 16.0	4
17		Heel	24	4.0, 8.0, 12.0, 16.0	4
18			48	4.0, 8.0, 12.0, 16.0	4
					72

6. Experimental procedures

Step (1): The seepage tank was adjusted horizontally by using a set of supports and a spirit level and makes sure that the seepage tank sides completely impervious, fig.(2).

Step (2): Filling the seepage tank with the sand layers as in natural field, a known size of dry sand was poured in the seepage tank and it was compacted by using a wooden hammer of cross section 10 x 10 cm and 30 cm height, each compacted layer have a constant thickness equal 15 cm. make sure before filling the seepage tank that the width of tank was constant and equal 30cm. Each type of sandy layer consists of two compacted layers. Finally, make sure that total depth of sandy layers equal 60 cm.

Step (3): Structure model was adjusted horizontally and it was fixed on the soil surface and the touch surface between soil layers and structure model was fully connected and no voids space between them.

Step (4): Sheet pile was adjusted vertically at the floor toe and it was established in soil layers with required experiments depth.

Step (5): Water was supplied at the upstream side of the seepage tank from the constant head tank by using the flow pipe 1.3 cm. The upstream and downstream water level was exactitude by using the over flow pipe

0.5 inch to obtain the different effective head, H. Minimum time required to reach to the steady state situation (constant seepage discharge …) was taken about 3.0 hours, it was estimated from the constant head permeability test . After this time, the results could be recorded.

Step (6): the drainage valve was opened to drain the water which was inside the seepage tank. That is to be sure there is no seepage coming through the space between the vertical sheet (gate) and the prespex sheet and between the floor and the prespex sheet, during the next test.

The drainage valve was closed when just the water head above the water surface equal to zero.

Step (7):

- For each value of effective water head steps no. 5 were repeated.
- For each value of sheet pile depth steps no. 3, 4, 5 and 6 were repeated.
- For each arrangement of soil layers, all steps from step no. 1 to step no. 6 were repeated.

7. RESULTS ANALYSIS

The results of experimental model were recorded as the piezometers reading along the length of the hydraulic structure foundation using six recording point.

The uplift pressure results clear that, when the hydraulic structure supported using the sheet pile foundation at any position under foundation floor the result uplift pressure increase with increasing the effective water head, figs. (3-a) and (3-b).

The uplift pressure decrease when the sheet pile location moves from the foundation toe toward the center of foundation length and increase when the sheet pile location moves from the center of foundation length toward the foundation heel and the uplift pressure results where the sheet pile was located at the foundation heel are more than the results where the sheet pile was located at the foundation toe, figs. (3-c) and (3-d).

The application point of the resulting uplift pressure force was nearer to the upstream side of the floor when the sheet pile locates at the mid-length of the floor, Movement of the sheet pile toward upstream or downstream end of the floor moves the application point toward the mid-length of the floor, that occur according to increase the uplift head values upstream sheet pile relative to its values at downstream side of the sheet pile, fig. (3-e).

The seepage discharge decrease by decreasing the effective water head and decrease by increasing the sheet pile penetration depth in soil layers, figs. (3-f) and (3-g). This relation expressed as a liner equation as shown:

$$\frac{Ho}{Hmax} = a \times \frac{qo}{qmax}$$

Where:

a : factor depend on the sheet pile depth relative to the total depth of soil layers.

The hydraulic gradient under the floor of hydraulic structure increases with increasing the effective water head, the values of hydraulic gradient have a slightly changes along the floor length, fig. (3-h).

The hydraulic gradient values increase from the toe to the heel of the floor and the hydraulic gradient values is converged near the sheet pile location, figs.(3-h) and (3-i).

The indicator color method was used to clear the stream lines of seepage flow under the hydraulic structure. Photo (1) cleared that, the resultant stream lines in case of the upper layer was medium sand and the lower one was coarse sand where sheet pile was located at the floor toe of hydraulic structure at the penetration depth 40% of total depth of soil layers.

8. Comparison between experimental and numerical results.

Photo (2) cleared that, the numerical model by the SEEP/W program in case of the upper soil layer is medium sand and the sheet pile was located at toe of the hydraulic structure floor by penetration depth is 60% of the total depth of soil layers. Photo (3) shown that, the result flow net after run the program and solve the numerical model.

8.1 The uplift pressure results.

In case of the upper layer is coarse sand and lower one is medium sand and the floor of hydraulic structure without sheet pile, it can be observed that increasing the effective water head on the hydraulic structure leads to increase of the uplift pressure, the experimental results is analogous the numerical results and more than it with small difference. Also, the uplift pressure head decreases along the floor length for experimental and numerical results, fig. (4-a).

In case of the floor of hydraulic structure is without sheet pile. it is obviously that the experimental and numerical results emphasize that there is no effect for the arrangement of soil layers in this case for the uplift pressure results, fig. (4-b).

8.2 The seepage discharge results.

In case of the upper layer of soil is coarse sand and the lower one is medium sand for upstream sheet pile, it can be concluded that the numerical results of seepage discharge have the same trend of the experimental results. Also, the numerical and

experimental results emphasize that increasing the sheet pile penetration depth leads to decrease of seepage discharge and the difference between the numerical and experimental results of the seepage discharge by values can be neglected especially for high values of sheet pile depth, fig. (4-c).
In case of the floor with upstream sheet pile at depth less than the upper layer depth. From the numerical and experimental results, it can be concluded that increasing the permeability of the upper layer of soil leads to increase of the seepage discharge, fig. (4-d).
The difference of results between experimental work and numerical analytic with (SEEP/W program) decreases with decreasing of the effective water head for upstream sheet pile for any soil layers arrangement, figs. (4-c) and (4-d).

8.3 The hydraulic gradient results.

In case of the upper layer of soil is coarse sand and the lower one is medium sand and the floor of hydraulic structure without sheet pile, the hydraulic gradient increases with increasing of the effective water head. Also, the numerical results of hydraulic gradient were higher than the experimental results and the numerical results have the same trend of the experimental results, fig(4-e).
In case of the floor of hydraulic structure with upstream sheet pile penetrated both layers of soil beneath the floor. It can be observed that increasing the permeability of the upper layer leads to decrease of the hydraulic gradient, fig(4-f).

9. Conclusions

From the result relations after study the case of study experimentally and numerically, can be concluded that,

- To decrease the uplift pressure values under the hydraulic structure foundation can be use the sheet pile at foundation toe.
- Increasing the sheet pile depth causes
  - Decreasing the resultant uplift pressure and decreasing the resultant seepage discharge through the soil layers under the hydraulic structure floor either upstream or downstream sheet pile.
  - Increasing the uplift pressure values at upstream of the sheet pile and decreasing its values at downstream of the sheet pile when the sheet pile locates at the mid-length of the floor.
  - Decreasing the hydraulic gradient under the hydraulic structure floor, and changes the hydraulic gradient curve to linear gradual shape.
  - Movement the application point of the uplift pressure force toward the downstream side of floor either upstream or downstream sheet pile.
  - Movement the application point of the uplift pressure force toward the upstream side of floor when the sheet pile locates at the mid-length of the floor.
- Increase of the upper soil layer permeability lead to decreasing the result uplift pressure.
- Increasing of the sheet pile depth is more effective in case of (C/M) upper layer is coarse sand and lower one is medium sand, the decreasing percentage of the resulting seepage discharge reaches to 79.4 and 87.3 % when sheet pile depth relative to the total depth of soil layers are 0.60 and 0.80 respectively.
- The total uplift pressure force for any arrangement of soil layers is the same when the hydraulic structure floor constructs without sheet pile, but, the point of resultant uplift pressure application moves slightly toward the downstream side of floor when the upper layer is medium sand.
- The uplift pressure values in case of the hydraulic structure floor without sheet pile increases in the first half of the floor and decreases in the second half of the floor, when the permeability of the upper layer increases.
- The application point of the uplift pressure force under the hydraulic structure floor locates at the second quarter of the floor from the upstream side of floor for all cases of study.
- The application point of the uplift pressure force under the hydraulic structure floor moves toward the downstream side of floor if the sheet pile locates at the upstream or downstream side of the floor when permeability of the upper layer decreases.
- The application point of the uplift pressure force under the hydraulic structure floor moves toward the upstream side of floor if the sheet pile locates at the mid-length of the floor when the upper layer permeability decreases.
- The seepage discharge and the hydraulic gradient values increase with increasing the

permeability of the upper layer in case of the sheet pile only penetrate the upper layer.

- The seepage discharge and the hydraulic gradient values decrease with increasing the permeability of the upper layer in case of the sheet pile depth higher than the upper layer depth.

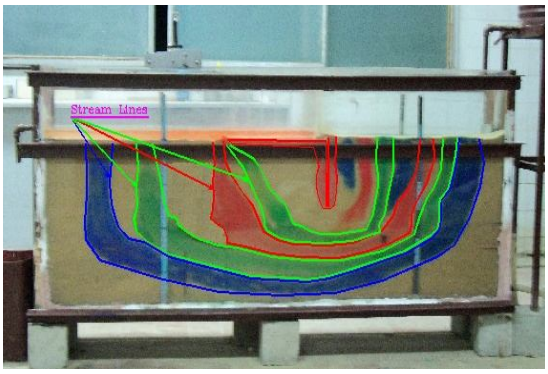

Photo (1): Stream line paths under floor, at M/C, H_o/H_{max}=1.00, S/D=0.40, X_s/L=0.00.

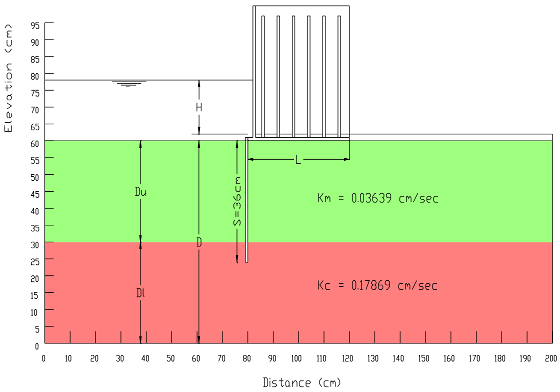

Photo (2): numerical (SEEP/W) model, at M/C, H_o/H_{max}=1.00, S/D=0.60, X_s/L=0.00.

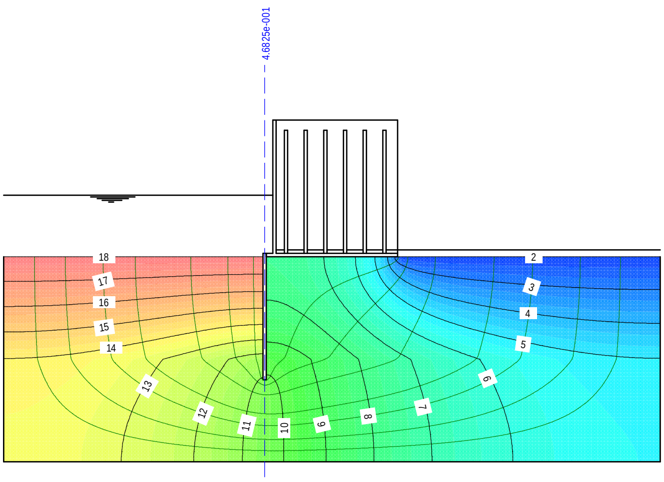

Photo (3): Flow net after (SEEP/W) analysis run.

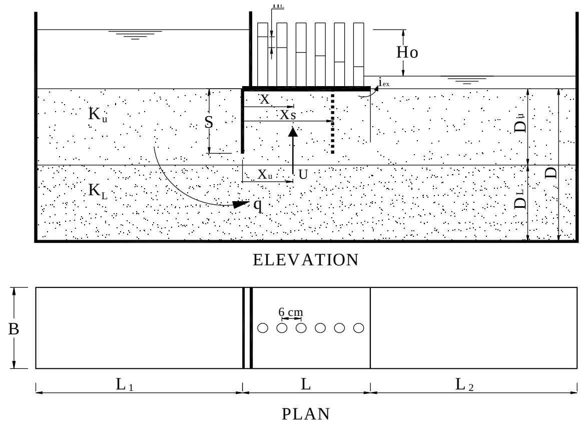

Fig.(1) : Sketch of the problem and defined parameters

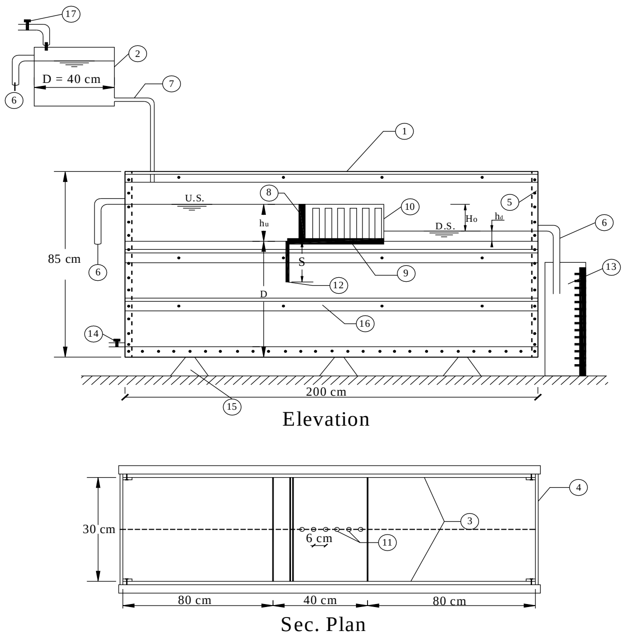

Fig.(2) : Schematic diagram of experimental model

1- Seepage Tank 200 ×85×30 cm.
2- Constant head tank.
3- Prespex Sides.
4- Steel Side.
5- Steel angles.
6- Over Flow Water Pipe .
7- Flow Pipe.
8- Prespex Gate 1.5cm thick.
9- Prespex floor 1.5 cm thick.
- 6 Pizometers.
11- Piezometer Nozzles 0.2 cm diameter.
12- Steel Sheet pile.
13- Graduated Tube.
14- To drainage system.
15- Supports.
16- Bracing angles.
17- Control Valve.

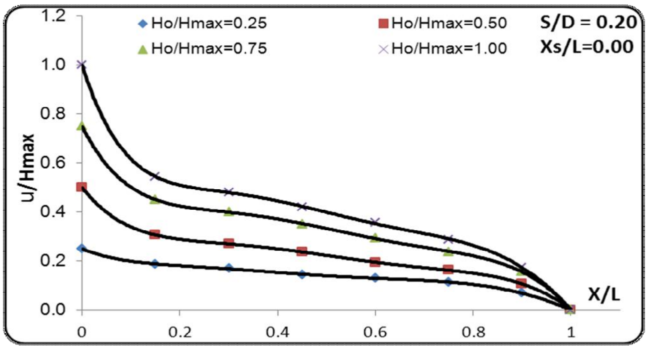

Fig.(3-a) relation between the uplift pressure and the effective water head.

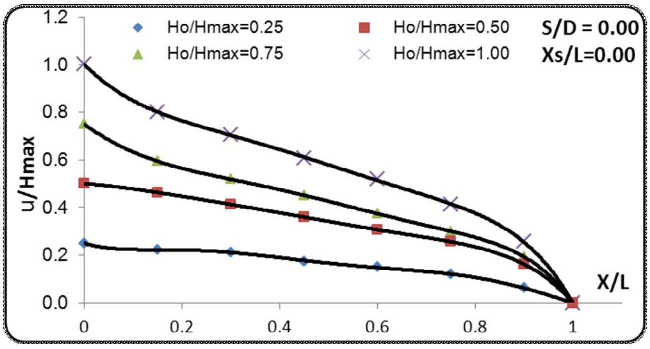

Fig.(3-b) relation between the uplift pressure and the effective water head.

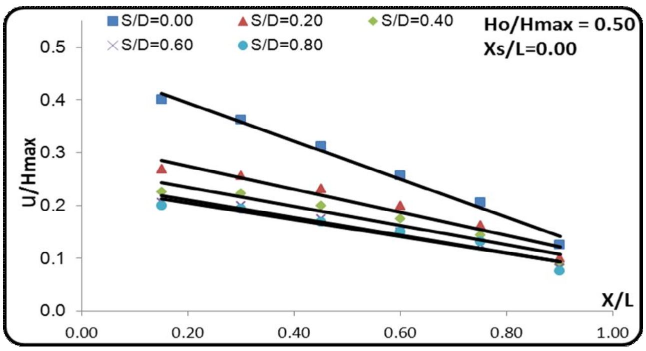

Fig.(3-c) relation between the uplift pressure and the sheet pile penetration depth.

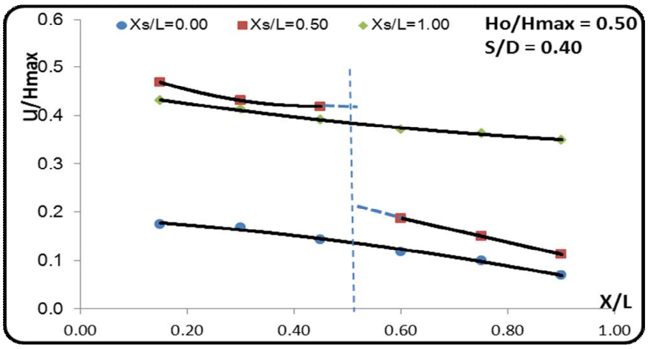

Fig.(3-d) relation between the uplift pressure and the sheet pile location.

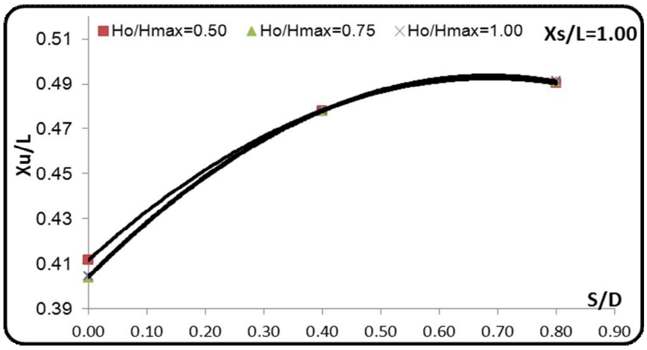

Fig.(3-e) Application point of the uplift pressure force for different values of sheet pile depth.

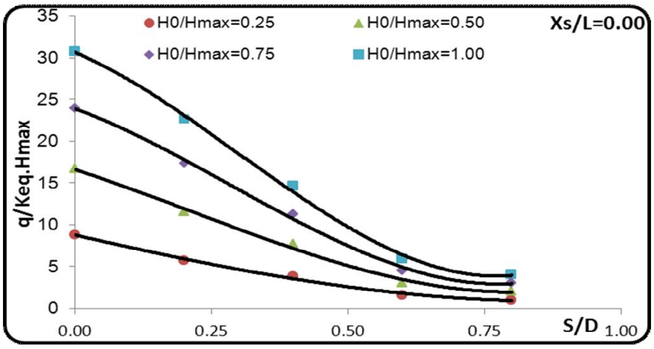

Fig.(3-f) relation between the relative seepage discharge and sheet pile penetration depth.

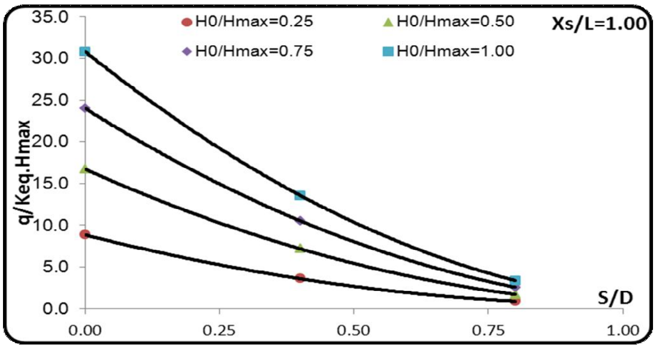

Fig.(3-g) relation between the relative seepage discharge and sheet pile penetration depth.

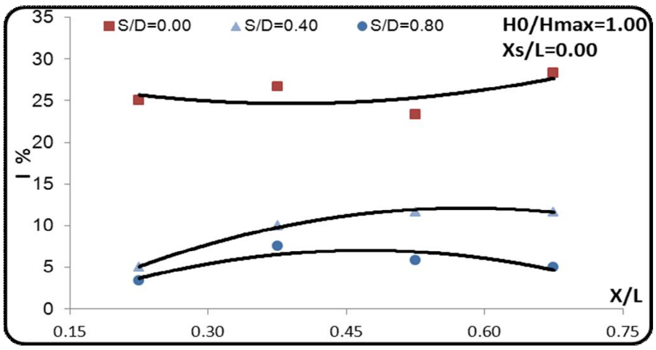

Fig.(3-h) relation between the hydraulic gradient and sheet pile penetration depth.

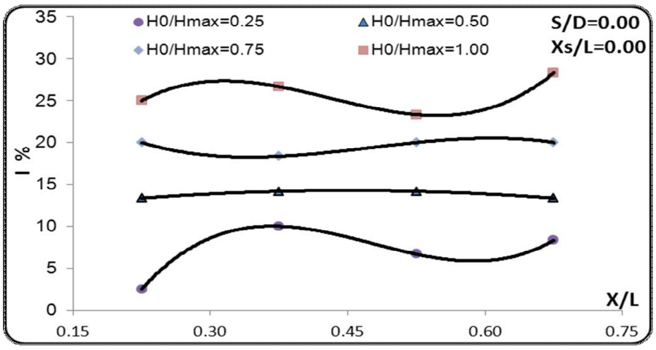

Fig.(3-i) relation between the hydraulic gradient and the effective water head.

Figure (3) Experimental results relations.

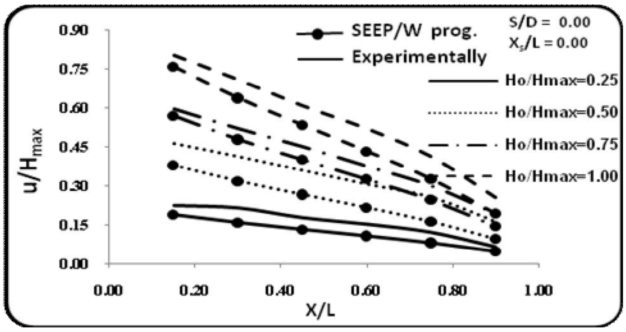

Fig.(4-a) The uplift pressure head in case of C/M.

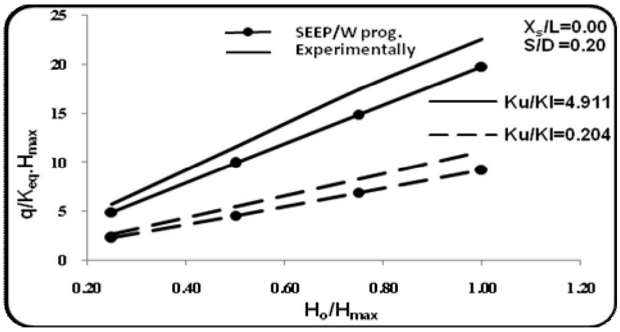

Fig.(4-d) The seepage discharge.

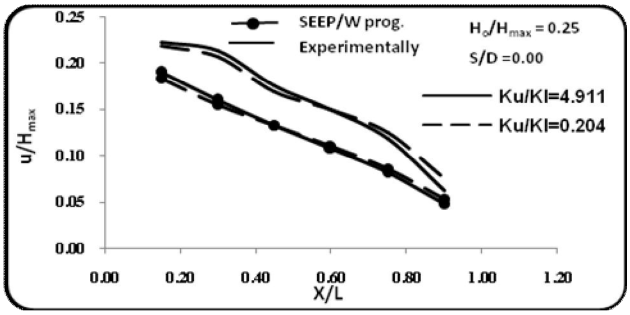

Fig.(4-b) The seepage discharge in case of C/M.

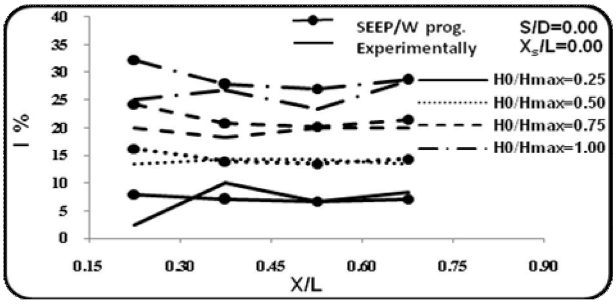

Fig.(4-e) The hydraulic gradient in case of C/M.

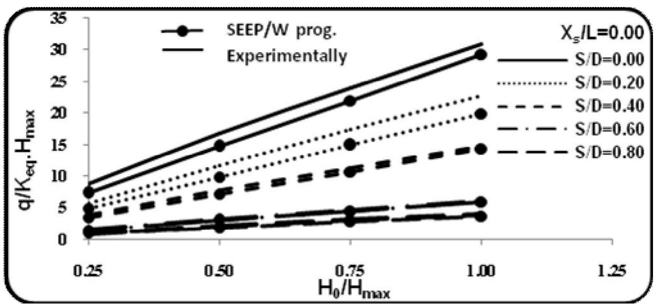

Fig.(4-c) The seepage discharge in case of C/M.

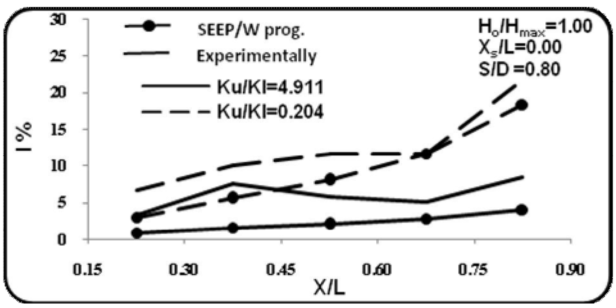

Fig.(4-f) The hydraulic gradient.

Figure (4) Comparison between experimental and numerical relations

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