# Evaluation of Seepage Length between Cutoffs under Heading up Structures founded on a Stratified Soil

Mohamed A. El-Molla[1], Mostafa A. Abdelaal[2] and Abd El-Kawy A. Khalifa[3]

[1] Assistant Lecturer, Civil Engineering Department, Higher Technological Institute, Egypt
[2] Associate Professor, Irrigation and Hydraulics Department, Faculty of Engineering, Al-Azhar University, Egypt
[3] Professor, Irrigation and Hydraulics Department, Faculty of Engineering, Ain Shams University, Egypt
Eng.m_anas@yahoo.com

**Abstract:** Seepage under the aprons of heading-up structures causes many problems like piping and excessive uplift pressure that can threaten the stability of the structures. Seepage can't be totally prevented but many seepage control methods are suggested to safeguard structures against the threats of seepage. Adding horizontal length to the apron, using sheet piles or using a drainage blanket downstream the structure's apron are among those methods. Using sheet piles under the aprons of heading-up structures is a well-known method that is used to increase the percolation length, decrease the hydraulic gradient and increase the structure's safety against piping and excessive uplift pressure. Sheet-piles can be used to decrease the horizontal length of the structure's aprons whenever needed due to either construction or economic reasons. According to Bligh's theory, the percolation length is calculated as the total sum of both the horizontal and the vertical lengths considering that both lengths have the same effect on the percolation. Lane's theory gives the seepage through a vertical length a weight equals 3 times the horizontal length. Different methods like conformal mapping technique, graphical method (flow net), experimental methods (sand tank models, Hele-shaw models, Electric Analogue models), analytical methods (fragment method), and Numerical methods (finite element, finite difference and Boundary element methods) can be used to solve seepage problems with different degrees of complexities and accuracies [Harr,1962; Serge Leliavsky, 1965; U.S. Army Corps of Engineers 1986; U.S. Army Corps of Engineers, 1999; and Mobasher, 2005]. The effect of sheet pile has been studied in many previous researches using the electric analogue method [El Salawy, El Molla and Bakry, 1997; El Salawy and El Molla, 2000; Mobasher, 2005; El Tahan, Shafik and El Molla, 2012]. Other studies used finite element method to investigate seepage under the aprons of heading up structures provided with a single sheet pile [El Molla, 2001; Hassan, 2004; Obead, 2013]. The soil layer under the apron is usually approximated to a single homogeneous layer to simplify the analysis. Soil is naturally not homogeneous as it is formed of layers that have different characteristics. In the present study, investigation of the horizontal path of the creep line between the cutoffs is to be done considering that the soil under the structure is formed of two horizontal layers. Multiple scenarios for the apron of heading-up structure, orientation of sheet piles and different ratios for the thicknesses and the hydraulic conductivities of the two soil layers have been investigated using a 2D finite element model (GMS-SEEP2D). 288 runs are conducted and analyzed for various scenarios for the aprons of hydraulic structures. The effect of presence of sheet piles (upstream and downstream) under the apron of a heading-up structure located on stratified soil that consists of two different horizontal layers on the seepage under the apron is investigated. A horizontal length equivalent to double the depths of sheet piles is added to the length of the apron and the resulting head loss due to the new length is compared to the head loss due to sheet piles. Six different ratios between the hydraulic conductivities of the two soil layers under the apron are studied, and Three (L/T) ratios are used for each ratio between the hydraulic conductivities of the two soil layers under the apron to analyze the effect of soil stratification on the results of the ratio between head loss with sheet piles under the apron and head loss without sheet piles under the apron ($R\%=\frac{\square}{\square}*100$). An experimental Electric analogue model is also used to study the same problem in order to verify the results of 2D numerical model. Results show that the assumption of the horizontal creep length under aprons having the same weight while designing aprons of hydraulic structures is a weak one. The head loss actually varies between the upstream and downstream sheet piles. So, design charts for stratified soil that consist of two layers are presented to be used as a tool in practical design for aprons of heading up structures formed on stratified soil and provided with upstream and downstream sheet piles at the ends of the apron. Good agreement is also found between the between the electric analogue model and numerical model SEEP2D results for both cases of single soil layer and stratified soil under the apron.

[Mohamed A. El-Molla, Mostafa A. Abdelaal and Abd El-Kawy A. Khalifa. **Evaluation of Seepage Length between Cutoffs under Heading up Structures founded on a Stratified Soil.** *Life Sci J* 2018;15(6):40-47]. ISSN: 1097-8135 (Print) / ISSN: 2372-613X (Online). http://www.lifesciencesite.com. 5. doi:10.7537/marslsj150618.05.

**Keywords:** Seepage; Finite element; SEEP2D; Heading-up structures; Sheet piles; Creep length, Stratified soil, electric analogue.

## Introduction

Seepage is a very important factor that affects the stability of a heading-up structure. Using sheet piles under the aprons of heading-up structures increases the percolation length, decreases the hydraulic gradient and accordingly provides more safety against piping and uplift under the structure's apron.

Different methods like conformal mapping technique, graphical method (flow net), experimental methods (sand tank models, Hele-shaw models, Electric Analogue models), analytical methods (fragment method), and Numerical methods (finite element, finite difference and Boundary element methods) can be used to solve seepage problems with different degrees of complexities and accuracies [Harr,1962; Serge Leliavsky, 1965; U.S. Army Corps of Engineers 1986; U.S. Army Corps of Engineers, 1999; and Mobasher, 2005]. The effect of sheet pile has been studied in many previous researches using the electric analogue method [El Salawy, El Molla and Bakry, 1997; El Salawy and El Molla, 2000; Mobasher, 2005; El Tahan, Shafik and El Molla, 2012]. Other studies used finite element method to investigate seepage under the aprons of heading up structures provided with a single sheet pile [El Molla, 2001; Hassan, 2004; Obead, 2013].

SEEP2D is a finite element program that has been applied in many researches to study seepage and has proved to be an efficient tool for seepage analysis [El Molla, 2001; Ozkan, 2003; Noori and Ismaeel, 2011; El Molla, 2012; El Molla, 2014; and others].

In this paper a 2D finite element model (SEEP2D) was used to investigate seepage under the apron of a heading-up structure formed on a stratified pervious soil that consists of two horizontal layers and provided with upstream and downstream sheet piles at its ends. Sensitivity analysis for the variables involved in the problem as well as different scenarios for the thickness of pervious layer under the apron, the length of the apron, and the depths of upstream and downstream sheet piles was performed.

## Description of the Model

SEEP2D is a 2D finite element (steady state) flow model. The two dimensions are the horizontal and vertical dimension (i.e., vertical profile). In a typical modelling problem involving the SEEP2D software, a series of tasks are performed in a specific sequence as follows:

1. Mesh generation.
2. Setting boundary conditions.
3. SEEP2D execution.
4. Post-processing the output.

The SEEP2D software was developed by the United States Army Engineer Waterways Experiment Station to model a variety of problems involving seepage. The governing equation used in the SEEP2D models is the Laplace equation. Transient or time varying problems and unconfined plan models cannot be modelled using SEEP2D. SEEP2D allows for different hydraulic conductivities along the major and minor axes (anisotropic conditions) to be defined [SEEP2D Primer, 1998]. Heterogeneous models can be created by specifying different values of hydraulic conductivity for the elements representing the different layers or regions. Post-processing includes contouring of the total head (equipotential lines), drawing flow vectors, and computing flow potential values at the nodes. These values can be used to plot flow lines together with the equipotential lines (i.e., flow nets). The phreatic surface can also be displayed [SEEP2D Primer, 1998].

## Dimensional Analysis

In the present study, all the variables involved in the problem can be expressed as:

$$\Phi(H, d_1, d_2, L, T, T_1, T_2, K_1, K_2, \rho, g, P_3, P_4) = 0$$

Where the notations are as defined in the previous section.

Applying Buckingham's π Theorem and taking H, ρ and g as the repeating variables, we can see that the number of variables affecting the phenomenon (n) equals 13, and the number of fundamental dimensions involved (m) equals 3 which are M, L and T, so the number of non-dimensional parameters (n – m) will be equal to 10.

We have 10 π terms which are:

$$\pi_1 = \frac{d_1}{H},\quad \pi_2 = \frac{d_2}{H},\quad \pi_3 = \frac{L}{H},\quad \pi_4 = \frac{T}{H},\quad \pi_5 = \frac{T_1}{H},\quad \pi_6 = \frac{T_2}{H},\quad \pi_7 = \frac{K_1}{\sqrt{g * H}},$$

$$\pi_8 = \frac{K_2}{\sqrt{g * H}},\quad \pi_9 = \frac{P3}{H},\quad \pi_{10} = \frac{P_4}{H}$$

From the previous π terms the functional relationship can be written as follows:

$$\Phi(\frac{d_1}{d_2},\frac{L}{H},\frac{T}{H},\frac{T_1}{H},\frac{T_2}{H},\frac{K_1}{\sqrt{g*H}},\frac{K_2}{\sqrt{g*H}},\frac{P_3}{L},\frac{P_4}{L})=0$$

Where (T) is the sum of ($T_1$) & ($T_2$) which have a constant value so the relationship is reduced to:

$$\Phi(\frac{d_1}{d_2},\frac{L}{H},\frac{T}{H},\frac{K_1}{\sqrt{g*H}},\frac{K_2}{\sqrt{g*H}},\frac{P_3}{L},\frac{P_4}{L})=0$$

Subtracting $P_4$ from $P_3$ the π terms become:

$$\Phi(\frac{d_1}{d_2},\frac{L}{H},\frac{T}{H},\frac{K_1}{\sqrt{g*H}},\frac{K_2}{\sqrt{g*H}},\frac{P_3-P_4}{L})=0$$

Let (S) be the head loss with sheet piles under the apron and (W) be Head loss without sheet piles under the apron.

$$\Phi(\frac{d_1}{d_2},\frac{L}{T},\frac{K_1}{\sqrt{g*H}},\frac{K_2}{\sqrt{g*H}},\frac{S}{L},\frac{W}{L})=0$$

Dividing the fifth term by the sixth term the functional reduces to:

$$\Phi(\frac{d_1}{d_2},\frac{L}{T},\frac{K_1}{\sqrt{g*H}},\frac{K_2}{\sqrt{g*H}},\frac{S}{W})=0$$

Ratio between head loss with sheet piles under the apron and head loss without sheet piles under the apron will be (R).

$$R=\frac{S}{W}$$

Dividing the second term by the third term the functional relationship reduces to:

$$\Phi(\frac{d_1}{d_2},\frac{L}{T},\frac{K_1}{\sqrt{g*H}},\frac{K_2}{\sqrt{g*H}},R)=0$$

Where $\sqrt{g*H}$ constant, by dividing the third term by the fourth term it reduced to the final functional relationship and can be written as:

$$\Phi(\frac{d_1}{d_2},\frac{L}{T},\frac{K_1}{K_2},R)=0$$

**Numerical Model Application**

It the present study, the horizontal path of the creep line between the sheet piles is to be investigated considering that the soil under the structure is formed of two horizontal layers. Multiple scenarios for the apron of heading-up structure, orientation and depths of sheet piles and different ratios for the thicknesses and hydraulic conductivities of the two soil layers have been investigated. 288 runs are conducted and analyzed for various scenarios for the aprons of hydraulic structures.

The difference between the water head upstream and downstream the structure is H. The floor/apron of the structure is of length L and provided with two sheet piles with depths $d_1$ and $d_2$ at its ends, where $d_1$ is the depth of the upstream sheet pile and $d_2$ is the depth of the downstream sheet pile. The depth of pervious soil layer under the apron is 15 m divided into two layers. This depth is chosen because it was shown in a previous research to have the greatest effect on the results. The soil under the apron consist of two layers of hydraulic conductivity $K_1$ and $K_2$ where $K_1$ is the hydraulic conductivity of the upper layer and $K_2$ is the hydraulic conductivity of the lower homogeneous pervious layer.

Six different scenarios for the ratio ($K_1/K_2$) are studied through the present research (refer to Table (1-b). The values of $K_1$ and $K_2$ are chosen to represent four different types of soil as shown in Tables (1-a) [Stibinger, 2014]:

Table (1-a): The values of hydraulic conductivities of different soil types.

Table (1-b): The values of hydraulic conductivities of upper and lower layers and the ratio between them.

Table (1-a)

| | **$K_1/K_2$** | **$K_1$** | **$K_2$** |
|---|---|---|---|
| | | **m/day** | **m/day** |
| **1** | 0.1 | 0.001 | 0.01 |
| | 10 | 0.01 | 0.001 |
| **2** | 0.01 | 0.01 | 1 |
| | 100 | 1 | 0.01 |
| **3** | 0.02 | 0.01 | 0.5 |
| | 50 | 0.5 | 0.01 |

Table (1-b)

| **K** | **Soil Type** |
|---|---|
| 0.001 | till |
| 0.01 | clay |
| 1 | fine sand |
| 0.5 | loamy soil |

Calibration and verification of the model were made in a previous research and the model's results were found to be accurate and reliable.

**Experimental Work**

The electric analogue model used in this research consists of a glass tank of dimensions 60 cm * 20 cm. for the case of stratified soil, two soil layers with depth 10 cm each are considered and separated by a perforated plastic strip that has copper wires filling the perforations in order to pass the electric current between the two layers without mixing the salt solution and tap water together (refer to figure (8)).

The dimensions of electric analogue are related to the dimensions of numerical model by a scaling ratio equals 1.3. The sheet piles lengths used are 7.8, 5.2, 3.25 and 2 cm which correspond to the values used in the numerical model (6, 4, 2.5 and 1.5 cm). The same scaling ratio is used for the horizontal lengths.

Comparing the results of the two models as shown in the following table and figures (9) to (11), showed good agreement as the results are found to be very close at most measured points.

**Table (3): Comparison between electric analogue model and SEEP2D results**

| **Layers** | **$d_1/d_2$** | **R %** | | **$K_1/K_2$** |
|---|---|---|---|---|
| | | **SEEP2D** | **Experimental** | |
| **One** | **4** | 88.39 | 81.82 | 1 |
| | **2.67** | 91 | 88.04 | |
| | **2.4** | 81.61 | 79.31 | |
| | **1.6** | 87.19 | 80 | |
| **Two** | **4** | 70.21 | 62.05 | $K_1>K_2$ |
| | **2.67** | 71.76 | 71.71 | |
| | **2.4** | 72.07 | 65.92 | |
| | **1.6** | 73.04 | 70.47 | |
| **Two** | **4** | 70.21 | 71.96 | $K_1<K_2$ |
| | **2.67** | 71.76 | 78.2 | |
| | **2.4** | 72.07 | 66.33 | |
| | **1.6** | 73.04 | 75.44 | |

**Results Analysis**

The value of the ratio between head loss with sheet piles under the apron and head loss without sheet piles under the apron (R %) against ($d_1/d_2$) for the different (L/T) ratios is plotted (refer to figures (5), (6) and (7)). The value of R% due to changing ($K_1/K_2$) for the average values at different (L/T) ratio is also plotted (refer to figure (12)).

Plotting the ratio (R %) against the ratio between the depths of upstream and downstream sheet piles respectively ($d_1/d_2$) for different values of ($K_1/K_2$), as shown in figures (5 to 7). it is noticed that the ratio (R) slightly decreases with the increase in the ratio between ($d_1/d_2$). Also, it is obvious that changing the ratio of ($K_1/K_2$) has no effect on (R), while from figure (12), the change in the ratio ($K_1/K_2$) has a very slight effect on (R %). The ratio (R %) in the case of two layers is less than that of one layer for the same (L/T) by about 15% to 25%. That means that for the case of two layers, the horizontal length (L) between the U.S sheet pile and D.S sheet pile should be increased 15% to 25% than for the case of one layer.

Figure (13) chose the ratio between head loss with sheet piles under the apron and head loss without sheet piles under the apron (R %) against the ratio between upstream and downstream sheet piles depths ($d_1/d_2$) for different values of (L/T), it is noticed that (R %) slightly decreases with the increase of ($d_1/d_2$) for all values of (L/T).

From figure (14) it is noticed that the ratio (R %) is directly proportional with the ratio (L/T) for both cases one layer and two layers.

Two equations were concluded to express the relations of (R %) for the cases of single homogeneous pervious soil layer and two pervious soil layers under the aprons follows:

For the case of single homogeneous pervious soil layer under the apron equation (1) can be used:

$$R\% = 59.609*\left(\frac{L}{T}\right) - 23.813\left(\frac{L}{T}\right)^2 + 55.947 \ldots \text{eq. (1)}$$

For the case of two pervious soil layers under the apron equation (2) can be used:

$$R\% = 94.663\left(\frac{L}{T}\right) - 32.039\left(\frac{L}{T}\right)^2 + 10.389 \ldots \text{eq. (2)}$$

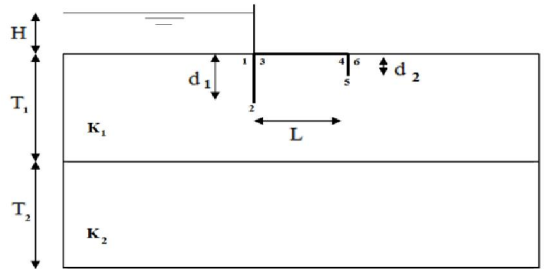


**Figure (1): The variables involved in the problem with two sheet piles.**

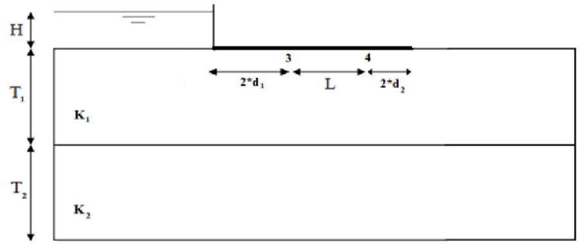


**Figure (2): The variables involved in the problem without two sheet piles.**

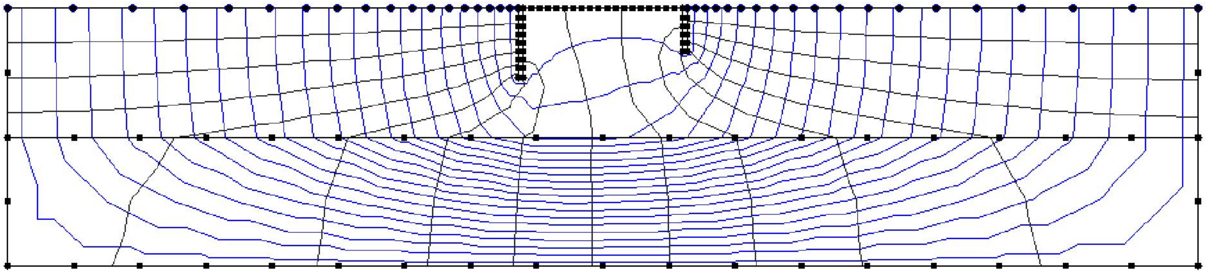


**Figure (3): Sample of flow net obtained from SEEP2D for two layers with sheet pile where K1/K2=0.1. (SEEP2D output)**

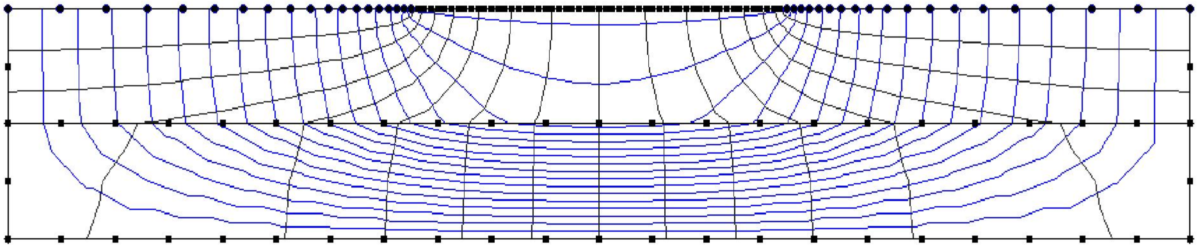


**Figure (4): Sample of flow net obtained from SEEP2D for one layer without sheet pile where K1/K2=0.1. (SEEP2D output)**

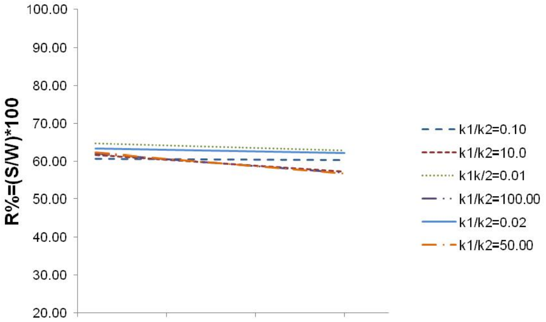


**Figure (5): R% ratios by changing (d1/d2) for L/T=0.67**

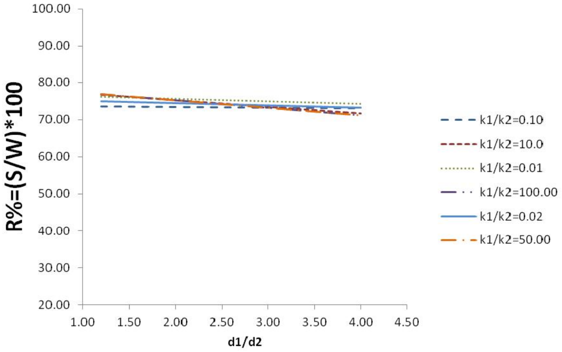
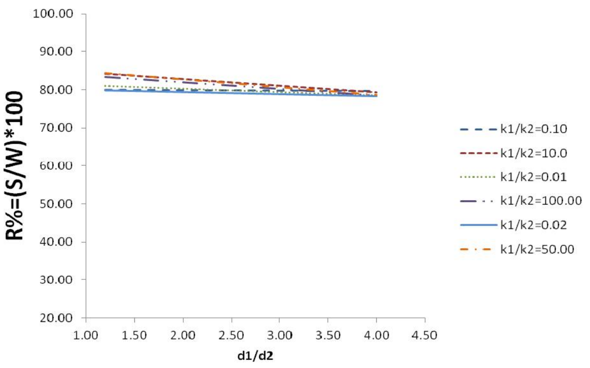
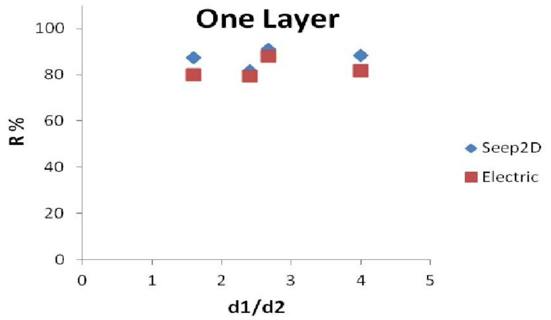
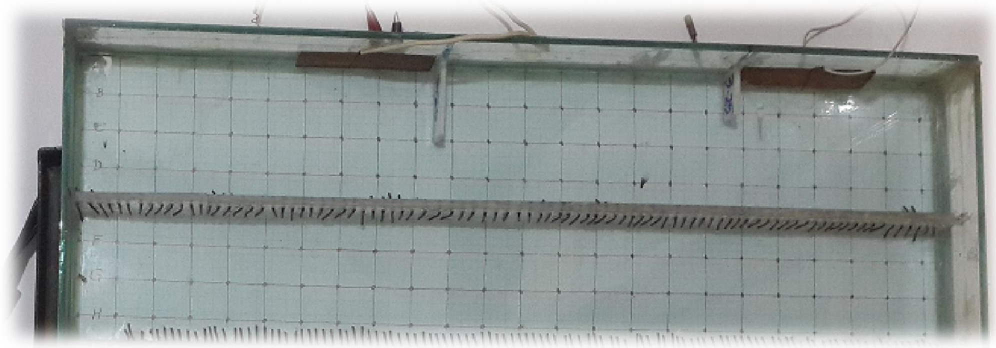
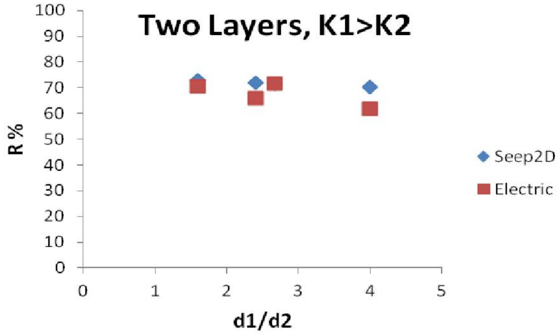


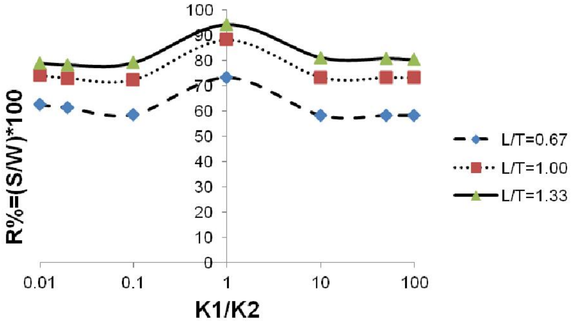
**Figure (6): R% ratios against (d1/d2) for L/T=1.00**











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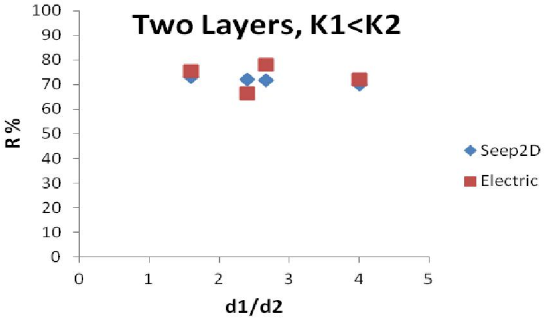

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model and SEEP2D results for two soil layer, $K_1<K_2$

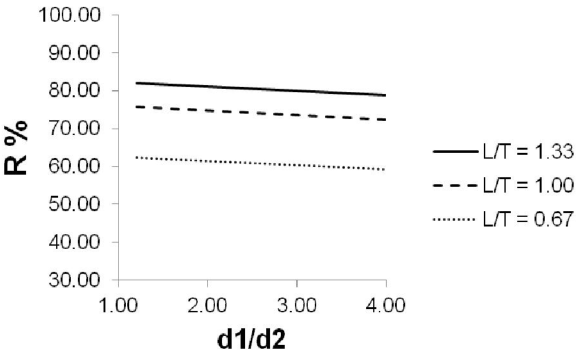

**Figure (13): R% ratios against ($d_1/d_2$) for different (L/T) Values.**

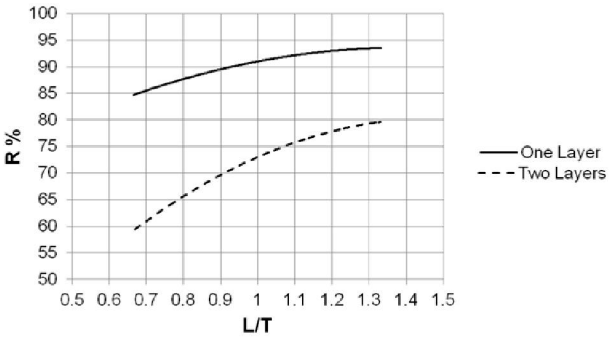

**Figure (14): R% ratios against (L/T) for single layer and two layers.**

## Conclusions

1. Two equations are derived to calculate (R %) (the ratio of head loss with sheet piles under the apron and head loss without sheet piles under the apron) as a function of (L/T).
2. For the case of two layers changing the ratio ($K_1/K_2$) affects the ratio (R %).
3. The ratio ($d_1/d_2$) has a slight effect on (R %) in the case of two layers.
4. The ratio (R %) in the case of two layers is found to be within the range of 15 % to 25 % greater than the ratio (R %) in the case of one layer.
5. It was noticed that the change of hydraulic gradient along the apron's length is different than the change along the soil length at the two ends.
6. For small depths of (3 to 6 m) for U.S and of (2.5 to 3.5 m) for D.S sheet piles it was noticed that the horizontal creep length has greater effect on the head loss compared to bigger depths of both U.S and D.S sheet piles.
7. It is recommended to consider soil stratification carefully when evaluating the effect of sheet piles on creep length for cases similar to the studied cases in the present research.
8. The electric analogue model and numerical model SEEP2D results for both cases of single soil layer and stratified soil under the apron showed good agreement.

## Notations

$d_1$ = Depth of upstream sheet pile from its point of intersection with the apron to its toe level (m).

$d_2$ = Depth of downstream sheet pile from its point of intersection with the apron to its toe level (m).

g = Gravitational acceleration by ($m/s^2$).

H = Head difference between upstream and downstream the apron by (m).

$K_1$= Hydraulic conductivity of the upper homogeneous pervious stratum by (m/h).

$K_2$= Hydraulic conductivity of the lower homogeneous pervious stratum by (m/h).

L = Horizontal distance between the upstream and downstream sheet piles by (m).

$P_3$= Head at point (3) by (m).

$P_4$= Head at point (4) by (m).

($P_3$-$P_4$) = Difference of the head between U.S sheet pile and D.S Sheet pile by (m).

T = Total thickness of the pervious soil under the apron (sum of the thicknesses of the two homogeneous pervious strata) (m).

$T_1$ = Thickness of the upper homogeneous pervious stratum under the apron (m).

$T_2$ = Thickness of the lower homogeneous pervious stratum (m).

ρ = Density of seeping water by (N/m3).

S= Head loss with sheet piles under the apron (m).

W= Head loss without sheet piles under the apron (m).

R %= Ratio between head loss with sheet piles under the apron and head loss without sheet piles under the apron.

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