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Numerical Investigation of Creep Length under Effect of Cutoffs in Hydraulic Structures

M. Abdelaal[1], H.Ahmed[2], D. El Molla [3] and M. Anas[4]
1,2 Associate Professor, Irrigation and Hydraulics Dep., Faculty of Engineering, Al-Azhar University.
3 Lecturer, Irrigation and Hydraulics Dep., Faculty of Engineering, Ain Shams University.
4 Assistant Lecturer, Civil Engineering Dep., Higher Technological Institute.

ملخص البحث:

في هذا البحث تم استخدام نموذج ثنائي الأبعاد من العناصر المتناهية لدراسة تأثير وجود القواطع الرأسية علي خط زحف المياه أسفل فروشات منشآت الحجز والمؤسسة على طبقة من التربة المنفذة للماء. تم اختيار أبعاد مختلفة لسمك الطبقة المنفذة للماء تحت فروشات منشآت الحجز، كما تم دراسة تأثير طول الزحف الفعلي في حالات مختلفة لوجود قواطع رأسية أوعدم وجودها مع زيادة لطول فروشات منشآت الحجز بقيمة تساوي مجموع أعماق القواطع الرأسية الأمامية والخلفية.

بعد عمل النماذج الأولى لحالات الفروشات المزودة بقواطع والمؤسسة على تربة متجانسة (طبقة واحدة) ولها معامل نفاذية (K) واحدة والتي أجريت على عدد (144) نموذج تم أخذ قراءاتها ووضعها في جداول، ثم عمل تمثيل لأهم المتغيرات التي تؤثر في العلاقة بين وجود القواطع أسفل فروشات المنشآت المائية في أوضاعها ونسبها المختلفة وذلك في صورة منحنيات ومعادلات مرفقة، حيث تم مناقشة هذه النتائج بأسلوب علمي لبيان أثر هذه المتغيرات على كل نموذج ثم بيان الظواهر المشتركة على جميع النماذج التي تم دراستها.

وقد خلص البحث إلي أن وجود القواطع الرأسية أسفل فروشات المنشآت المائية تؤثر على كفاءة المسافات الأفقية بينها في تبديد طاقة خط الزحف بنسب تتراوح بين 0.73 في حالة "طول المسافة بين القاطعين / سمك الطبقة" (L/T=0.3) إلى 0.94 في حالة (L/T=1.33). كما أن وجود القواطع في الأمام تؤثر على كفاءة تبديد طاقة خط الزحف بنسبة أكبر من وجودها في الخلف (أي أن وجود القاطع الأمامي له نسبة أكبر في التأثير على المسافة الأفقية بين القاطعين من القاطع الخلفي). كما أن وجود قاطعين يؤثر بنسبة أكبر على كفاءة المسافة الأفقية من حالة وجود قاطع واحد.

و يوصي البحث أنه يجب الحذر والتدقيق في حساب المسافات الأفقية من طول خط الزحف الفعال المزود بقواطع رأسية وكذلك مراعاة نسب تأثير استخدام هذه القواطع في المسافات الأفقية بينها عند تصميم فروشات المنشآت الهيدروليكية المزودة بقواطع رأسية.

ABSTRACT

In this study a 2D finite element model (GMS- SEEP2D) is used to study the effect of presence of sheet piles (upstream or downstream or both together) under the apron of a heading-up structure on the seepage under the apron. The sheet piles are removed and a horizontal length equivalent to double the depths of sheet piles is added to the length of the apron in order to determine the effect of sheet piles on the efficiency of horizontal length between them. The resulting head loss due to the horizontal equivalent length is compared to the head loss due to sheet piles. 144 runs are conducted and analyzed for various scenarios considering having sheet piles in the upstream, downstream or both together or no sheet piles and adding an equivalent horizontal length to the apron of heading-up structure.

The presence of vertical sheet piles under the aprons of heading up structures is found to affect the efficiency of horizontal distance between them. The upstream sheet pile affects the efficiency of horizontal distance more than the downstream sheet pile. And the existence of two sheet piles has bigger effect on the efficiency of horizontal distance than using one sheet pile.

A chart relating the ratio between head loss with presence of sheet piles under the apron and head loss without sheet piles under the apron (R%) for different ratios of upstream and downstream sheet piles depths (d_1/d_2) was obtained. An equation is also derived to calculate the difference in the values of head loss in the case of using a sheet pile compared to the case of adding an equivalent horizontal length to the apron. A solved example on how to apply the equation is provided too.

KEYWORDS: Seepage; Finite element; Heading-up structures; Sheet piles; Creep length.

1. INTRODUCTION

Seepage is one of the most important factors that should be considered carefully during the design of heading structures. Seepage of water under the aprons of heading-up structures causes many problems like piping and excessive uplift pressure that can threaten the stability of the structure. Sheet piles are used under the aprons of heading-up structures to increases the percolation length and decreases the hydraulic gradient and hence safeguard the structure against piping and excessive uplift pressure under its apron. Sheet-piles can be used to decrease the horizontal length of the aprons whenever needed due to either construction or economic reasons.

Referring to Bligh's theory, the percolation length is calculated as the total sum of both the horizontal and the vertical lengths which mean that both lengths have the same effect on the percolation. Lane's theory states that the effect of vertical lengths on percolation is equal to three times the effect of horizontal lengths. No previous studies considered the effect of sheet piles under the aprons of heading up structures on the efficiency of horizontal distance between the sheet piles to dissipate the energy of the seeping water beneath these aprons.

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 [ElSalawy, ElMolla and Bakry, 1997; ElSalawy and ElMolla, 2000; Mobasher, 2005; El Tahan, Shafik and ElMolla, 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 (GMS- SEEP2D) is used to study the effect of presence of sheet piles (upstream or downstream or both together) under the apron of a heading-up structure on the seepage under the apron. The sheet piles are removed and a horizontal length equivalent to double the depths of sheet piles is added to the length of the apron in order to determine the effect of sheet piles on the efficiency of horizontal length between them. The resulting head loss due to the horizontal equivalent length is compared to the head loss due to sheet piles. 144 runs are conducted and analyzed for various scenarios considering having sheet piles in the upstream, downstream or both together or no sheet piles and adding an equivalent horizontal length to the apron of heading-up structure.

1. 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].

2. DIMENSIONAL ANALYSIS

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

$$\Phi(H, d_1, d_2, L, T, K, \rho, g, P_1, P_2, P_3, P_4, P_5, P_6) = 0$$

Where the notations are as defined at the end of the paper.

Applying Buckingham's π Theorem and taking H, ρ and g as the repeating variables, the number of non-dimensional parameters will be equal to 11.

$$\pi_1 = \frac{d_1}{H},\ \pi_2 = \frac{d_2}{H},\ \pi_3 = \frac{L}{H},\ \pi_4 = \frac{T}{H},\ \pi_5 = \frac{k}{\sqrt{g * H}},\ \pi_6 = \frac{P_1}{H},\ \pi_7 = \frac{P_2}{H},$$

$$\pi_8 = \frac{P3}{H},\ \pi_9 = \frac{P_4}{H},\ \pi_{10} = \frac{P_5}{H},\ \pi_{11} = \frac{P_6}{H}$$

The π terms are reduced to:

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

Let (S) be the head loss with sheet piles under the apron and (W) be Head loss without sheet piles under the apron (adding a horizontal length equivalent to double the depths of sheet piles to the apron). 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 reduced to:

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

Where K is constant, finally the functional relationship can be written as:

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

3. MODEL APPLICATION

In the present work SEEP2D model was applied to study the effect of existence of sheet-piles on the efficiency of horizontal length between them to decrease the seeping water's gradient. The apron is first provided with upstream and downstream sheet piles at the ends, then the sheet piles are removed and a horizontal length equivalent to double the depths of sheet piles is added to the length of the apron. The model consists of a heading up structure formed on a pervious soil layer with thickness T. The head difference between upstream and downstream the structure is H. The depths of upstream and downstream sheet piles are d_1 and d_2 successively. The horizontal distance between the upstream and downstream sheet piles is L. A total of 144 runs are conducted for various scenarios considering having sheet piles in the upstream only, downstream only, both upstream and downstream together or removing sheet piles and adding an equivalent horizontal length to the apron of heading-up structure.

4.1.CALIBRATION OF THE MODEL

To calibrate the model experimental readings which are results from previous studies conducted on an electric analogue model that have 2 sheet piles under an apron of a heading-up structure are used and compared to the results obtained from the studied 2D numerical model [El Tahan, 2012].

Three different mesh cell sizes were used and their readings were compared to readings obtained from a previous electric analogue study [El Tahan, Shafik and ElMolla, 2012], in order to verify the numerical model and select the hydraulic conductivity and mesh cell size.

Three values for H were used through the numerical modelling program, these were H= 3, 4, 6 m. L was taken 20m while d_1 and d_2 were taken 5m.

Figure (2) show a sample of model calibration which represents the head readings at first and last points [AboulAtta, 2015].

4.2.VERIFICATION OF THE MODEL

The model is verified by another set of electric analogue experimental readings for the same dimensions and conditions this time the length of apron L was taken 19m, the depth of the upstream sheet pile d_1 was taken 5m, and the depth of the downstream sheet pile d_2 was taken 2.5m.

Two values for H were used through the second set of numerical modelling program, these were H= 3, 7.5 m. From the results it is noticed that the point at the end of the apron had the biggest percentage of error, this may be due to ionization of water in the electric analogue model which happens near the cathode copper plate [AboulAtta, 2015].

4.3.SENSITIVITY ANALYSIS

Three different thicknesses for the soil layer are studied to analyze the effect of the thickness of soil layer 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%). The depth that has the greatest effect on the results (T=15m) is chosen to be used through the rest of the research work (Figure (3)).

4. RESULTS ANALYSIS

The studied scenarios are analysed and the effect of having sheet piles or an equivalent horizontal length for the apron of heading-up structure on the the efficiency of horizontal length between them to decrease the seeping water’s gradient is studied.

A chart relating the ratio between head loss with sheet piles under the apron and head loss without sheet piles under the apron (R%) for different ratios of upstream and downstream sheet piles depths (d1/d2) is obtained (Figure (4))

An equation is derived to calculate the difference in the values of head loss in the case of using a sheet pile compared to the case of adding an equivalent horizontal length to the apron. A solved example on how to apply the equation is also provided.

$$R\% = -23.813(\frac{L}{T})^2 + 59.609\left(\frac{L}{T}\right) + 55.947$$

5. EXAMPLE

Considering a structure that is formed on a pervious layer of 20 m thickness and has an apron of length 25 m (L/T=1.25m) using the provided equation R%= $\frac{S}{W}$ *100 = 93.25%

This means that using upstream and downstream sheet piles at the ends of the apron decreases the efficiency of percolation length by 93.25% than using no sheet piles and having an equivalent horizontal length.

6. CONCLUSIONS

Analysis of the data obtained from the model leads to the following conclusions:

- The presence of vertical sheet piles under the aprons of heading up structures affect the efficiency of horizontal distance between them with a ratio that ranges between 0.73 for (L/T) = 0.3 to 0.94 for (L/T) = 1.33
- Upstream sheet piles have greater effect than downstream sheet piles on the efficiency of creep line head dissipation (i.e. the upstream sheet pile affects the efficiency of horizontal distance between sheet piles more than the downstream sheet pile).
- The existence of two sheet piles has bigger effect on the efficiency of horizontal distance than using one sheet pile.
- The horizontal distances must be chosen and calculated carefully while calculating the effective percolation length for aprons that are provided with sheet piles
- The effect of sheet piles on the efficiency of the horizontal length between them must be considered when designing aprons of heading up structures.
- An equation is derived to calculate the difference in the values of head loss in the case of using a sheet pile compared to the case of adding an equivalent horizontal length to the apron and a solved example on how to apply the equation is also provided.

NOTATIONS

d1= Depth of upstream sheet pile from its point of intersection with the apron to its toe level (m).

d2 = Depth of downstream sheet pile from its point of intersection with the apron to its toe level (m).

g = Gravitational acceleration by (m/s2)

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

K= Hydraulic conductivity of the homogeneous pervious stratum of thickness (T) under the apron by (m/h).

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

P1= Head at point (1) by (m).

P2= Head at point (2) by (m).

P3= Head at point (3) by (m).

P4= Head at point (4) by (m).

P5= Head at point (5) by (m).

P6= Head at point (6) by (m).

P1-P2 = Difference of the head along the outer face of U.S Sheet by (m).

P2-P3 = Difference of the head along the inner face U.S Sheet pile by (m).

P4-P5 = Difference of the head along the inner face of D.S Sheet pile by (m).

P5-P6 = Difference of the head along the outer face D.S Sheet pile by (m).

T = Thickness of pervious stratum under the apron by (m).

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

R= Ratio between head loss with sheet piles under the apron and head loss without sheet piles under the apron (%) (R%= $\frac{S}{W}$ *100)

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

W= Head loss without sheet piles under the apron (adding a horizontal length equivalent to double the depths of sheet piles to the apron) (m)

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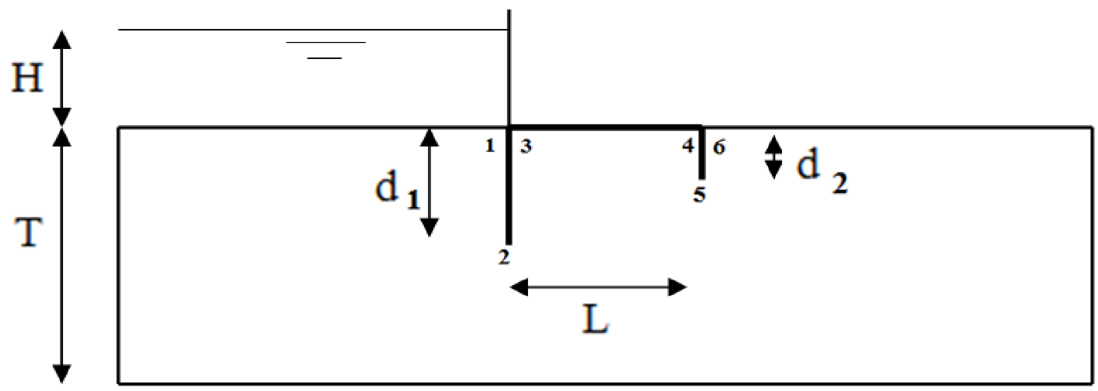

Figure (1): The variables involved in the problem.

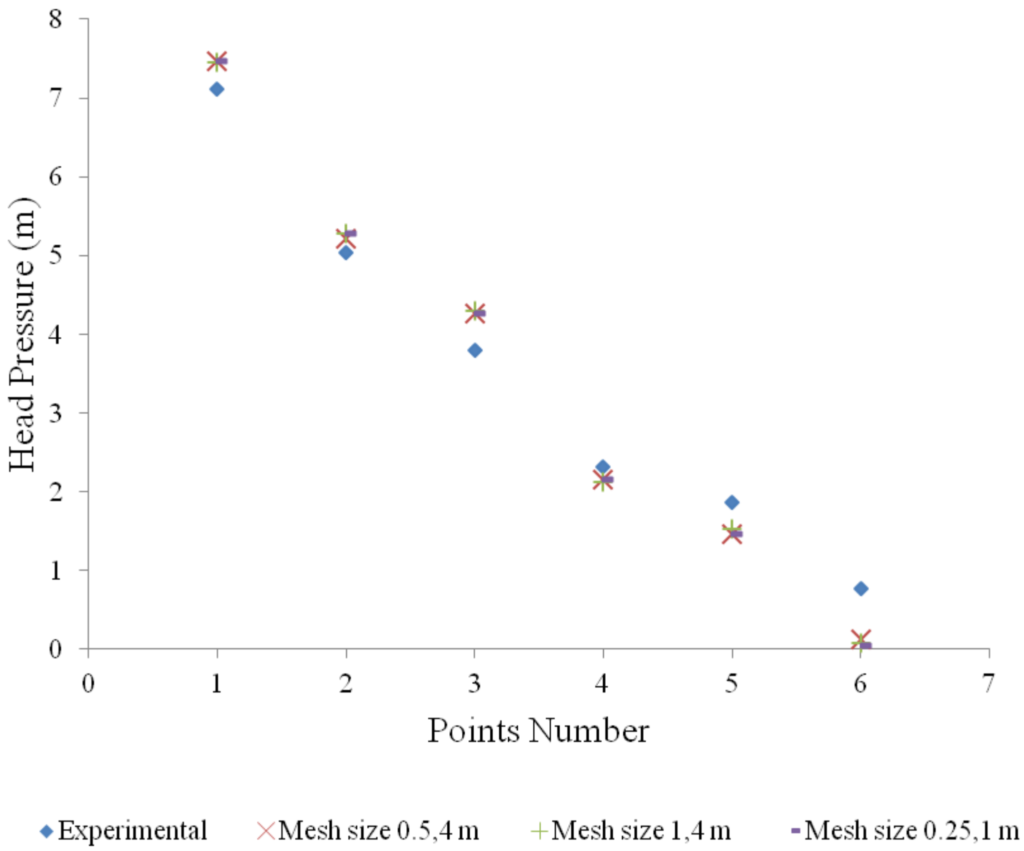

Figure (2): Sample of model calibration.

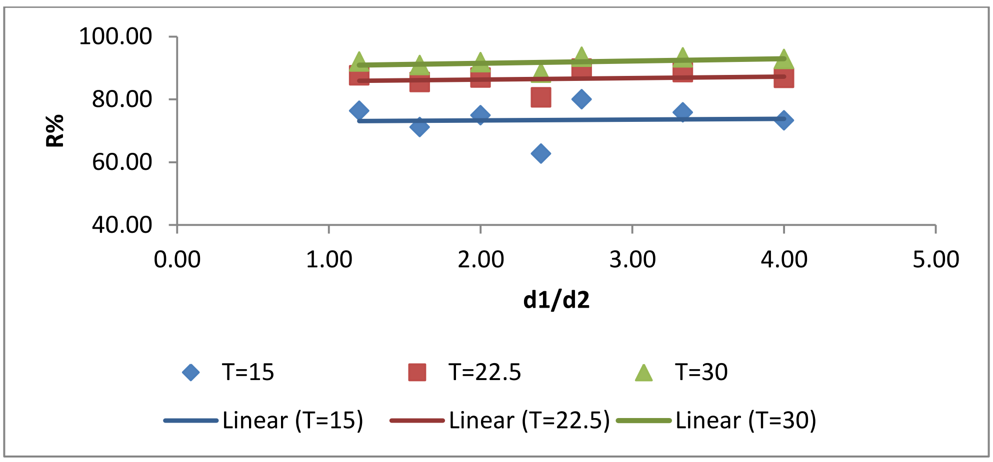

Figure (3): Effect of the thickness of soil layer on the ratio between head loss with sheet piles under the apron and head loss without sheet piles under the apron and adding an equivalent horizontal length to the apron (R%= $\frac{S}{W}$ *100)

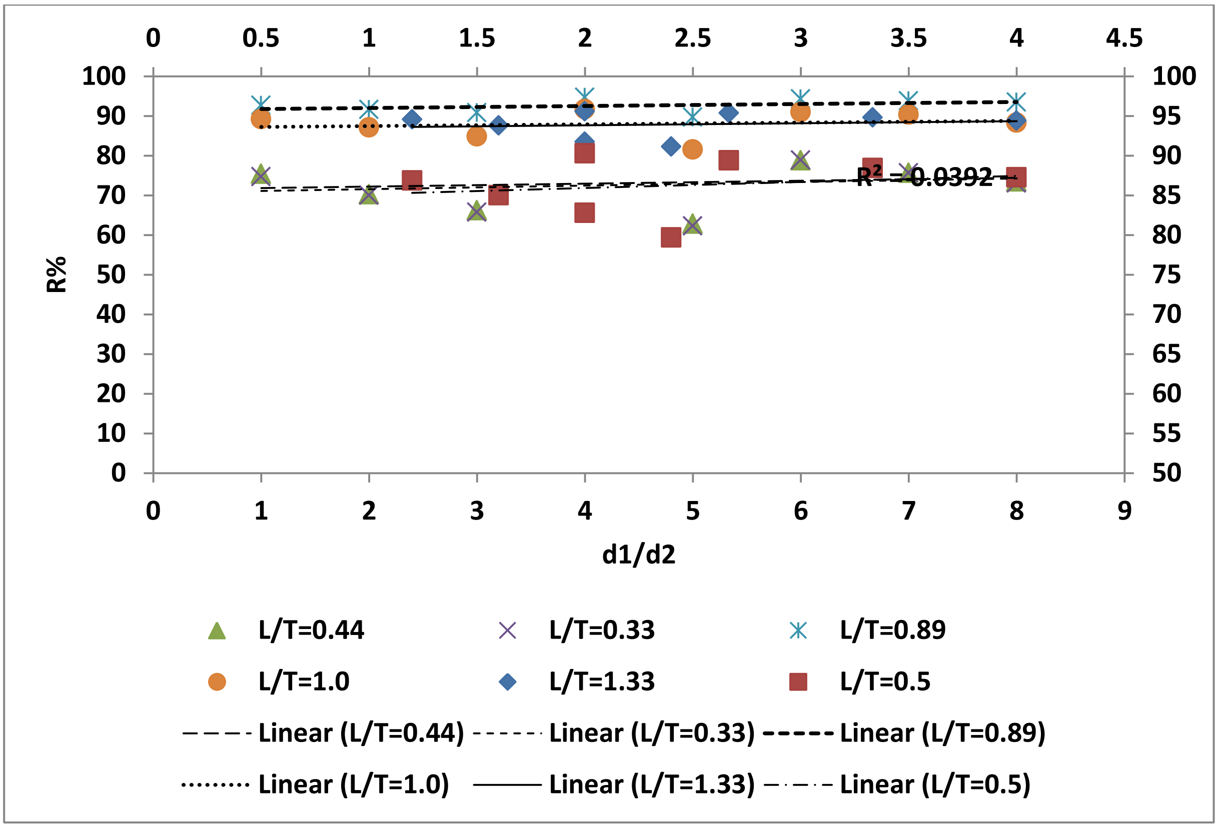

Figure (4): The ratio between head loss with sheet piles under the apron and head loss without sheet piles under the apron (R% = $\frac{S}{W}$)*100 for different ratios of upstream and downstream sheet piles depths (d1/d2)