Minimizing of seepage beneath earth fill dams using cutoff wall

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Earth fill dams must be constructed to stand safe and stable against the acting forces, in particular, that based on pervious foundations. Seepage flow beneath such dams presents the most dangerous effects on dam stability. To avoid these effects, the seepage flow must be controlled. One of the most efficient control methods is providing the dam with a cutoff wall, specially those based on pervious foundation of moderate finite depth. In the present work, the effect of the main parameters, on the seepage characteristics was studied, such as, the cutoff wall depth, the foundation depth, and effective head. The effect of the above parameters on the seepage discharge, the loss of head along the cutoff wall, and the height of seepage surface was analyzed numerically using the finite element model. A computer program was prepared to handle with input and output data. Results showed that the cutoff wall has a great effect on the seepage characteristics beneath an earth dam based on a pervious foundation of a finite depth. The obtained results are presented in a dimensionless form either through graphs or empirical equations, given in a dimensional form.

تنشأ السدود لتخزين مياه الأنهار وكذلك مياه امطار المتجمعة في الوديان الطبيعية لاستفادة منها في أنشطة الحياة المختلفة. ومن أكثر السدود إنتشاراهي السدود الترابية، وذلك لتوافر مواد إنشائها في الموقع. ويجب أن تنشأ السدود الترابية لتكون آمنة وثابتة ومستقرة ضد القوى المؤثرة عليها ومن أخطرالقوى التي تؤثر علي السدود الترابية تلك القوى الناتجة عن التسرب خلال تلك السدود، وكذلك أسفلها، خاصة المقامة منها علي تربة منفذة. وللتسرب خلال أو تحت السدود الترابية تأثير سيئ عليها، حيث يتولد عنه ظاهرة الانهيار التحتي المتمثلة في خروج حبيبات التربة المكونة لسد مع المياه المتسربة بظاهرتي الأنهيار الأنبوبي أو النهيار الكتلي. إضافة إلي ذلك فإن التسرب يؤدى إلي فقدان وضياع كميات كبيرة من المياه المختزنة. ولحماية السدود الترابية من هذه الأخطار يجب تقليل التسرب خلال هذه السود وأسفلها. وتوجد طرق كثيرة للإيفاء بهذا الغرض، ومن أكثر هذه الطرق ملائمة هو تزويد السد بحائط قاطع من مادة غير منفذة. والدراسة الحالية تهتم بتأثير وجود الحائط القاطع علي خصائص التسرب، وأهمها كمية المياه المفقودة بالتسرب، وكذلك الجهد المفقود نتيجة وجود الحائط القاطع. وقد تمت الدراسة باستخدام النموذج العددى المبني علي نظرية العناصر المحدودة من خلال برنامج حاسوب معد لذلك. وقد صيغت النتائج في منحنيات لابعدية، وصيغت أيضا في معادلات تجريبية يمكن استخدامها بسهولة.

Keywords: Earth dams, Seepage beneath and through earth dams, Control of seepage, Cutoff wall, Free surface

1. Introduction

One of the most important problem facing the world today is the provision, in the long term, of adequate supplies of fresh water to be used in different life activities. Inherent in this problem is the avoidance of waste, one serious aspect of which is the loss of valuable water carried to sea in flood. To maintain such waste water, dams, in particular earth ones, must be constructed on natural canyons and water streams.

Earth dams must be constructed to stand safe and stable against the effects resulting by the acting forces. The most dangerous effects that may lead to failure of earth dams is that raised due to seepage flow through or beneath such structures.

Foundation soil for dams often consists of recent alluvial deposits composed of relatively pervious sands and gravels overlying impervious geological formations. Two basic problems are found in pervious foundation; one pertains to the amount of under seepage, while the other is concerned with the stability of such structures.

The flow of water through a pervious foundation produces seepage force as a result of friction between the percolating water and the walls of the soil pores through which it flows. Such a seepage force is proportional to the hydraulic gradient resulting from the decrease in potential head due friction losses.

As the water upwardly percolates through the exit face, the resulting seepage force tends to lift the soil particles causing undermining of soil forming, the foundation and the dam embankment.

To reduce the effect of seepage force, the dam is provided with a cutoff wall as shown in fig. 1. Cutoff wall is an impervious barrier which functions as extension of the embankment core into the foundation .

The present study focuses on minimizing of seepage flow beneath earth dams.The problem under consideration here is to study the characteristics of seepage beneath an earth dam, founded on pervious foundation of intermediate depth, when provided with a cutoff wall located at its mid-point, as shown in fig. 1.

The study aims to investigate the effect of the various parameters on the seepage characteristics represented by; (i) the quantity of seepage discharge (*q*), (ii) the head loss along the cutoff wall (ΔH), and (iii) the minimum length of the toe filters located on the downstream slope (l).

The problem is solved numerically using the Finite Element Method (FEM). A computer program has been developed to prepare the required input and output data and to handle the obtained results. The finite element model was checked using the analytical solution presented for idealized cases of seepage flow through and beneath earth dams based on pervious foundations.

The problem of seepage either beneath or through earth dams has been extensively studied in different ways of approach [2-5, 7]. Such studies were interested by the analytical solutions for homogeneous earth dam based on impervious or pervious foundation .Later , some studies were focused on the seepage characteristics through earth dams provided with toe filter [8] and cutoff wall, experimentally using the Hele-Shaw model [10-12], and numerically using the finite element method [6, 13].

2. Problem definition and assumptions

The physical model for a seepage flow through and beneath an earth dam, founded on pervious foundation layer, is shown in fig 1. The dimensions of dam embankment are defined as follows:
The top width, b.
The base width, L.
The dam height, H_d.
The dam slopes, m_1 and m_2.

Such dimensions were kept constant throughout this study.

With reference to fig. 1, the parameters involved in the current study may written as follows:

- *T* Depth of pervious foundation layer,
- *H* Effective head acting on the seepage flow,
- *S* Depth of the cutoff wall, measured from the dam base line, and
- *K* Hydraulic conductivity.

The above mentioned variables will affect the characteristics of the seepage through and beneath an earth dam based on pervious foundation soil. Such seepage characteristics include the following items:
i- The seepage discharge passing through the pervious layer, q_s.
ii- The seepage discharge entering the filter, q_f
iii- The total seepage discharge through and beneath the dam,

$$q_t = q_s + q_f \, .$$

iv- The loss of head along the cutoff wall, ΔH, and
v- The height of seepage face h_3.

To simplify the problem the following assumptions are introduced:

The dam and supporting soil are of the same homogeneous and isotropic material, overlying an impervious layer. In this case the permeability coefficient is denoted as K_s.
- The heel and toe points of dam base are of the same elevation.
- The soil is fully saturated.
- Downstream face of the dam is acting as a filter.
- The total seepage discharge is divided into; seepage discharge entering. The filter, q_f, and

seepage discharge through to the soil layers, q_s.
- Pressure along the free surface is considered atmospheric.

3. The numerical model

In the present work, the numerical model is based on the FEM as illustrated by Bear [1], and Reddy [10].

The seepage flow through or beneath an earth dam presents a two dimensional (2D) flow problem, described by partial differential quations. The major advantage of the FEM is the ability to easily simulate a flow system with complex physical geometry and a wide variety of boundary conditions. However, discrimination errors are introduced by describing the continuous function of seepage flow in terms of values on some form of discrete grid. Furthermore, approximations are introduced in the digital approach by dividing the time into discrete steps. With care, errors due to such approximations can be made sufficiently small to be neglected. The finite elements mesh consists of simple 2D elements having shapes of triangles, and / or rectangles, connected to each other at nodal points on the boundaries of the elements.

4. Boundary conditions

Boundary Conditions must be determined before solving of equations, where in analyzing seepage problems the boundary conditions are the head or the flux at external points. There are two main types of boundary conditions, known as Dirichlet and Neumann conditions, where the head takes known values on the Dirichlet boundary conditions. Neumann conditions occurred over impermeable boundary in which no water crosses the boundary.

As illustrated in fig. 2, the boundary conditions, in the considered problem, may be arranged as follows:

4.1. Pervious boundaries

The upstream seepage face ABC presents the first equipotential line, thus the pressure along the boundary ABC are constant $\frac{\partial h}{\partial x} = 0$, where

$$h = T + h_1 = \text{constant}. \quad (1)$$

Also, the downstream exit seepage face GHI presents the last equipotential line, therefore,

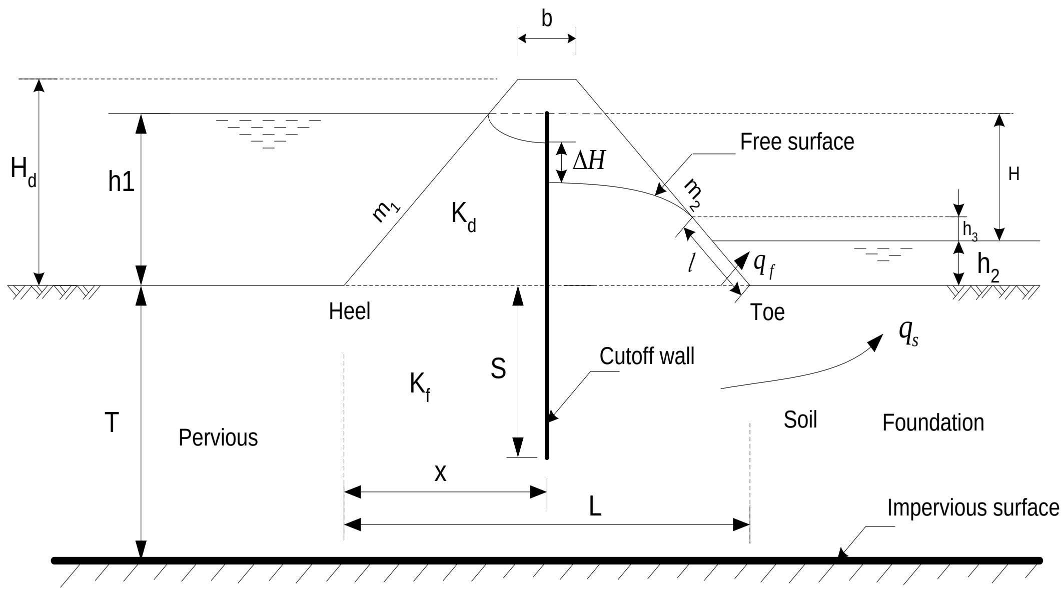

Fig. 1. Minimize of seepage beneath an earth dam using cutoff wall.

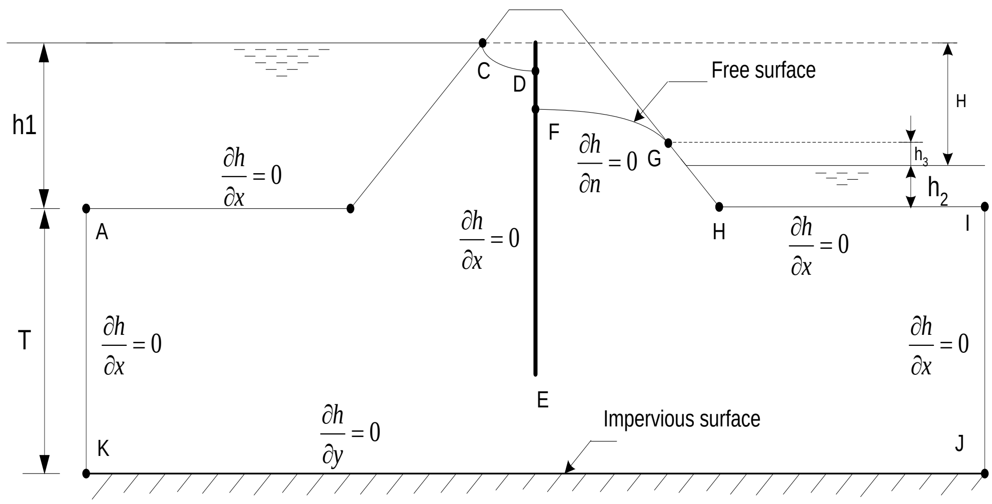

Fig. 2. Boundary conditions.

pressure along boundary GHI are constant and $\frac{\partial h}{\partial x} = 0$, where

$$h = T + h_2 = \text{constant}. \quad (2)$$

4.2. Impervious boundaries

Along the boundary Jk; $\frac{\partial h}{\partial y} = 0$

Also along the line DEF $\frac{\partial h}{\partial x} = 0$.

4.3. Free surface

The free surface CD and FG presents a stream surface. Hence, the normal velocity equals zero, where

$$\frac{\partial h}{\partial n} = 0 . \quad (3)$$

Since the pressure on the free surface is assumed to be atmospheric and equals zero, then the following condition should be satisfied along the free surface;

$$H = y. \quad (4)$$

The whole flow domain is divided into number of elements. The properties of each element are represented by a matrix, called an element matrix. Assembling of all element matrices in a global matrix represents the properties of the whole domain. The boundary conditions are applied and the resulting system of equation is solved for unknowns. After that any other functions of these unknowns are computed. All nodes and elements are defined and numbered, and then nodal unknowns are defined, which satisfy the minimum boundary conditions. There are two system for numbering nodes and elements, local numbering system and global numbering system. The local system is used for defining the element properties and the global system is used when discussing the assembly of elements.

The finite element mesh of the current problem consists of triangular elements. Total of nodes and elements number varies according to each case considered. Fig. 3 show the finite element mesh.

Referring to fig 1, the dimensions of the earth dam model, used to construct the finite element mish are chosen as follows;

The top width, b =10 cm.

The base width, L =100 cm.

The dam height, H_d = 30 cm.

The slope of dam face, $m_1 = m_2 = 1.5$.

Other dimensions, such as; the effective head H, the depth of the pervious foundation layer T, and the depth of the cutoff wall S are varied and taken as illustrated in table 1.

Table 1
The tested values of the considered parameters

parameters	Fixed parameters	Variable parameters
H	b = 10 cm,	$\frac{T}{L}$ = =0.05,0.1,0.15,0.20,0.25
T	L = 100 cm	$\frac{T}{L}$ =0.2,0.4,0.6,0.8,1.0
S	$m_1 = m_2 = 1.5$	$\frac{S}{T}$ =0.0,0.2,0.4,0.6,0.8

5. Main parameter involved in the current problem

Referring to fig. 1 and the aforementioned assumptions, the main parameters affecting the characteristics of seepage through and beneath an earth dam are:
- The effective head, H.
- The top and base width of dam embankment, b and L, respectively.
- The height of dam embankment, H_d.
- The slope of dam faces m_1 and m_2.
- The depth of cutoff wall S.
- The depth of pervious foundation layer T.
- The hydraulic conductivity, ks.

The dimensions of dam embankment; b, L, H_d, m_1 and m_2 as well as the hydraulic conductivity k_s are kept constant throughout the study.

The characteristics of seepage through and beneath an earth dam are; the seepage discharge (q), the loss of head along the cutoff wall (ΔH), and the height of seepage surface h_3.

Thus, the characteristics of seepage through and beneath an earth dam are; q, ΔH, and h_3 may expressed as follows:

$$q = f_1(H,T,S,k_s) \ . \tag{5}$$

$$\Delta H = f_2(H,T,S) \ , \ \text{and} \tag{6}$$

$$h_3 = f_3(H,T,S) \ . \tag{7}$$

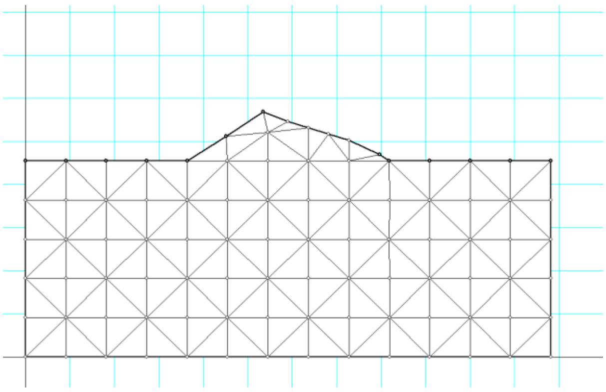

Fig. 3. Finite element mesh for seepage through and beneath an earth dam based on previous foundation.

Considering the base of the dam as reference parameter and using the dimensional analysis technique, the above seepage characteristics may be expressed as follows:

$$\frac{q}{k_s L} = f4\left(\frac{H}{L},\frac{T}{L},\frac{S}{T}\right) \ , \tag{8}$$

$$\frac{\Delta H}{L} = f5\left(\frac{H}{L},\frac{T}{L},\frac{S}{T}\right), \ \text{and} \tag{9}$$

$$\frac{h_3}{L} = f6\left(\frac{H}{L},\frac{T}{L},\frac{S}{T}\right) \ . \tag{10}$$

Referring to fig. 1, the tested values of the considered parameters, affecting the seepage characteristics in the considered problem, are given in tables 1.

6. Verification of finite element model

The finite elements model, is used to analyze the characteristics of seepage through and beneath an earth dam. The main target of this analysis is to find the values of the relative seepage discharge $\frac{q}{k_S}$, the loss of head along the cutoff wall, ΔH and the height of seepage surface h_3.

Considering an earth dam, without cutoff, based on a pervious foundation the analytical equations , presented by Grishin [3], and Nedrigy [7] were used to verify the numerical results obtained using the finite element model. Table 2 indicates the comparison between the result obtained using the analytical solution and those obtained using the numerical model.

7. Analysis of results and discussion

Analysis of results includes the effect of the main parameters on the seepage characteristics beneath an earth dam based on pervious foundation. Such effect includes;
- Effect of the depth of foundation soil, T,
- Effect of the depth of cutoff wall, S, and
- Effect of the effective head, H.

The resulting head loss, ΔH, due to existence of the cutoff wall, is the main target in controlling seepage flow beneath earth dam since satisfies four objectives:
- Decreasing the quantities of seepage discharge; q_t, q_s, and q_f.
- Lowering the free surface and hence decreasing the values of pore-water pressure acting on the probable slip circle leading to more stability of the dam slopes.
- Decreasing the exit area of flow above the dam toe which reduces the length of the required filter.
- Decreasing the seepage velocity at the exit surface and in turn decreasing the exit gradient and then reducing piping effect.

The effect of the considered parameters on the seepage characteristics is illustrated briefly as follows:

7.1. Effect of the considered parameters on the seepage discharge (q_s)

Referring to the dimensionless form of eq. (8), where,

$$q/K_S L = f_1\left(\frac{H}{L}, \frac{S}{T}, \frac{T}{L}\right),$$

The relative seepage discharge q/KsL is affected by the variation of the considered parameters H/L, S/T and T/L, as shown in fig. 4. The total discharge q_t/KsL increases as the relative head H/L increases, such effect is being clear when the relative foundation depth

Table 2
Comparison between analytical and numerical values of $\frac{q}{k}$ and h_3

H/L	Analytical solution				Numerical	
	Grishin		Nedrigy		present study	
	$\frac{q_t}{K_s}$	$h3$	$\frac{q_t}{K_s}$	h_3	$\frac{q_t}{K_s}$	h_3
0.05	2.2	0.29	3.55	0.37	2.368	0.350
0.10	4.85	0.66	7.38	0.88	5.470	0.80
0.15	8.05	1.11	11.98	1.6	9.51	1.40
0.20	11.89	1.69	17.8	2.6	14.32	2.15
0.25	16.53	2.44	22.7	4.0	18.18	3.15

T/L increases. This is referred to that; The increase of head increases the area of inlet face of flow which in turn increases the discharge.

Considering the effect of the relative depth of cutoff wall S/T, it is seen that the value of q_t/K_sL decreases as S/T increases with regard to the effect of the relative depth of foundation layers T/L. It is found that values of qt/K_sL rapidly increase due to increasing T/L up to $T/L \approx 0.8$, beyond which a slight increase is exist. The decrease in discharge with increasing the cutoff depth S is due to the effect of sheet pile. This is explained by the following two reasons; (i) the cutoff will decrease the passage area of flow under the dam leading to the contraction of stream lines which increase the head loss and in turn decrease the discharge (ii) the cutoff wall elongate the seepage path of flow since moves downwardly and upwardly around the cutoff which increases the head loss and decreases the discharge.

The discharge ratio q_f / q_t is also affected by the considered parameters, as shown in fig. 5.

Values of the relative discharge q_f/q_t increase as the relative head value H/L increases. Such increase is being obvious whenever values of T/L decrease.

As for the effect of S/T on values of q_f/q_t, it is indicated that the ratio q_f/q_t decreases when S/T increases. The rate of decrease in q_f/q_t due to increasing S/T is great for small values of T/L. Increasing the cutoff depth makes the

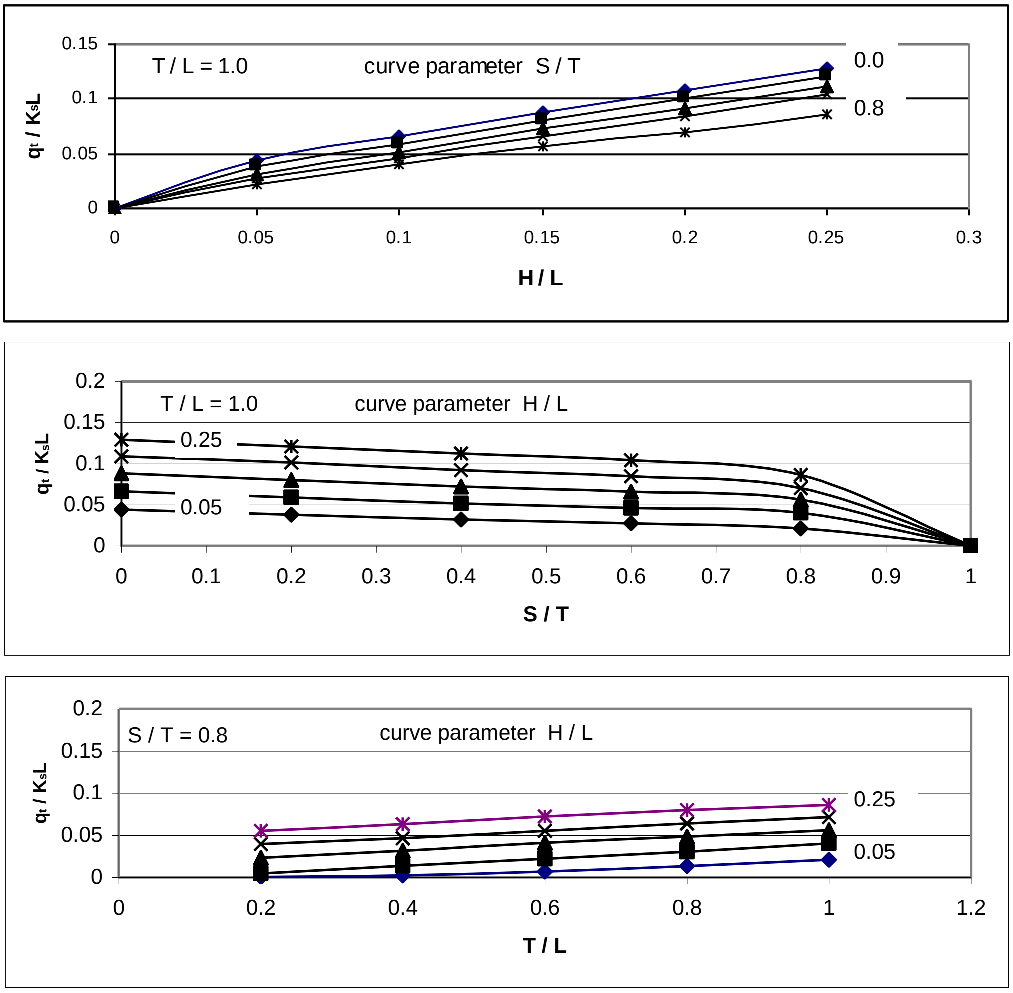

Fig. 4. Effect of the considered parameters on the seepage discharge (q_t / K_s).

flow to move away from the dam base which leading to increasing q_s and decreasing q_f.

The variation of values T/L affect the ratio q_f/q_t, since values of q_f/q_t greatly decreases due to increasing T/L, up to $T/L \approx 0.6$, beyond which a slight decrease is found. Increasing the foundation depth T increases the capacity of bearing layer q_s, leading to a decrease in value of q_f. It should be noticed that the main source of q_f is the wetted length of the upstream slope of the dam.

The percentage decrease, $\Delta q_t\%$, in values of q_t, within the variation of H/L due to increasing S/T, is given from

$$\Delta q_t\% = [(q_t) - (q_t)_c] \;/\; (q_t) \times 100. \tag{11}$$

Where (q_t) and $(q_t)_c$ are the total seepage discharge in case of dam without and with cutoff wall, respectively. It is seen from fig. 6 that values of $\Delta q\%$ increases due to increasing S/T, while it decreases when T/L increases.

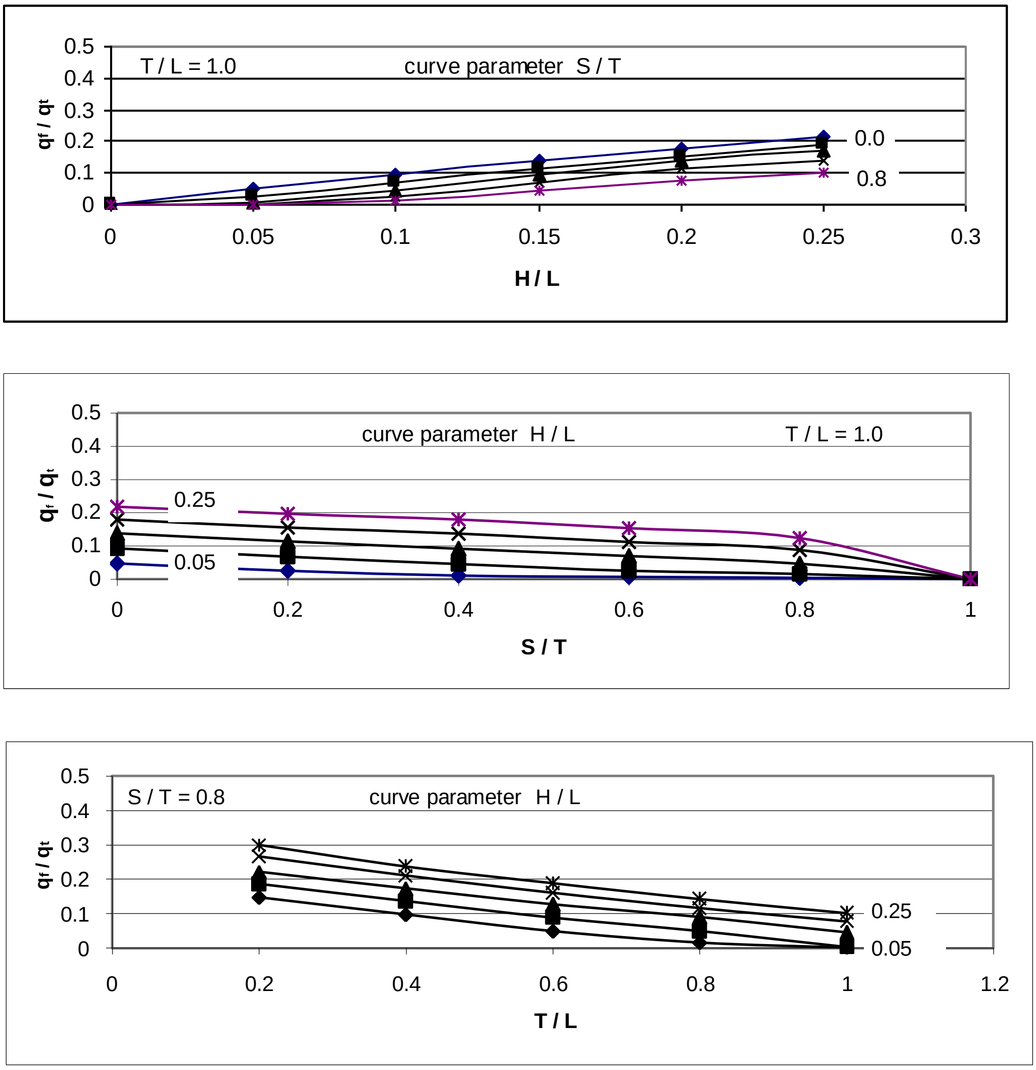

Fig. 5. Effect of the considered parameters on q_f/q_t

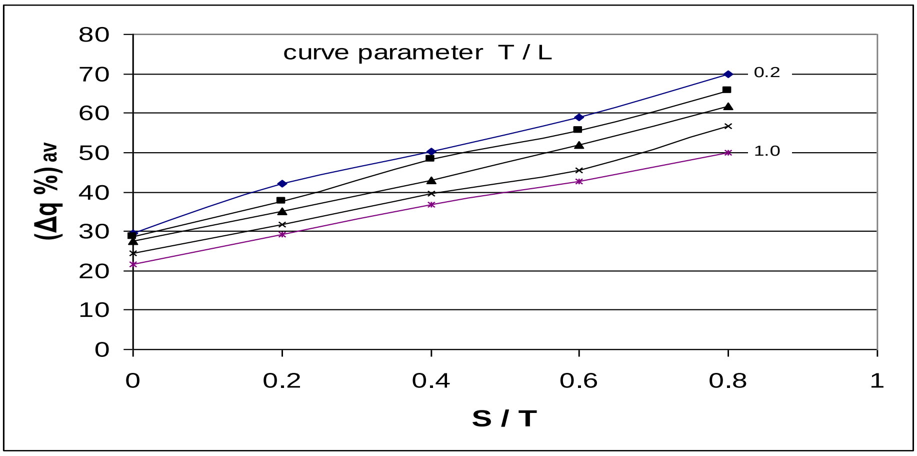

Fig. 6. The percentage decrease in the seepage discharge $\Delta q\%$, due to increasing S/T.

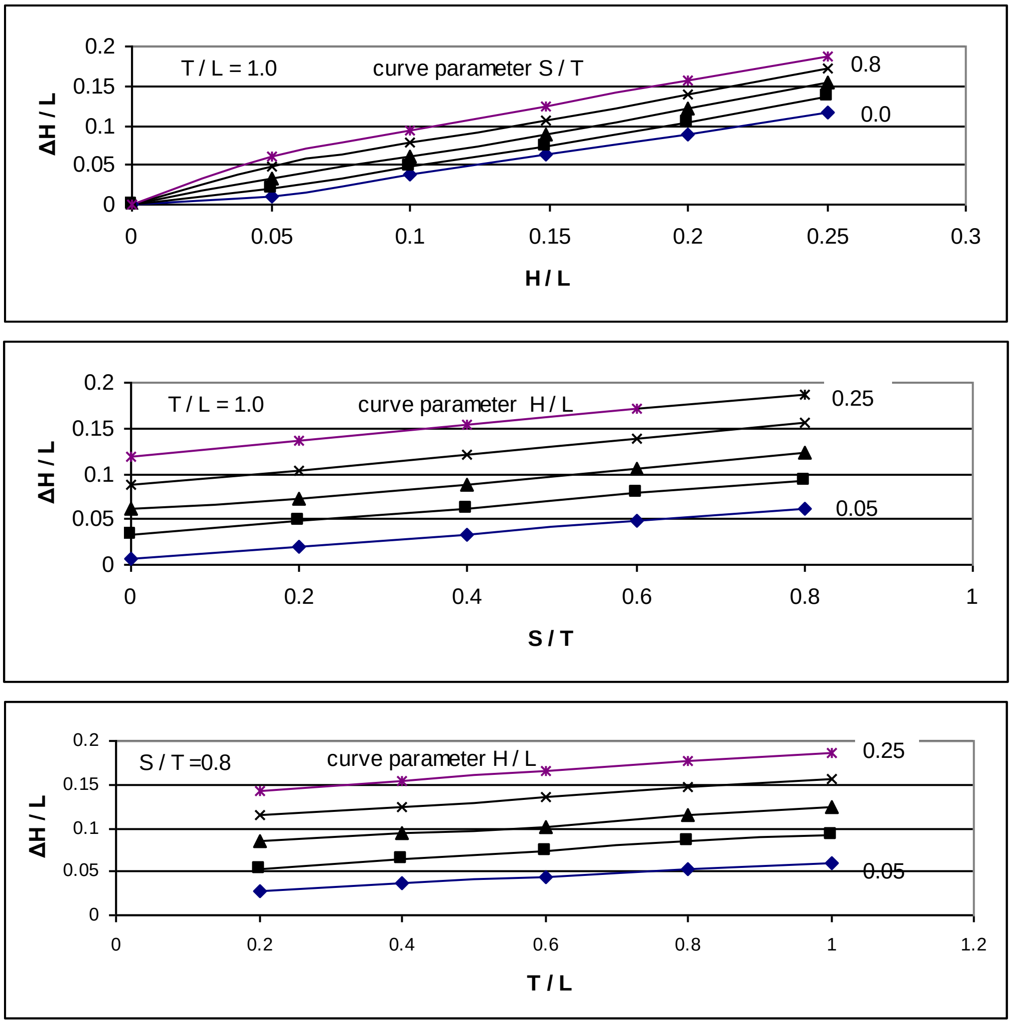

Fig. 7. Effect of the considered parameters on the loss of head ΔH.

With respect to effect of T/L it is obvious that variation of T/L value nearly has no effect on values of $\Delta H/L$ for S/T = 0.0 especially at small values of H/L. As S/T increases, values of $\Delta H/L$ slightly increase as T/L increases. As explained above, the increase in ΔH due to increasing S is referred to the head loss of flow caused by the cutoff. This is due to increasing the seepage path and decreasing the passage area of flow.

7.2. Effect of the considered parameter on the head loss due to cutoff wall (ΔH)

Eq. (9) indicates the dependence of the relative head loss, caused by the cutoff wall $\Delta H/L$, on the relative values of the acting head H/L, depth of cutoff wall S/T and depth of foundation layer T/L, as shown in fig. 7.

The value of $\Delta H/L$ increases as H/L increases. Such increase becomes noticeable whenever T/L increases.

With regard to effect of i on $\Delta H/L$ it is seen that $\Delta H/L$ values increase when value of S/T increases.

7.3. Effect of the considered parameters on the height of seepage surface (h_3)

The resulting effect due to variation of the values of the main parameters H/L, S/T and T/L on values of the relative height of seepage surface h_3/L is described in eq. (10) where,

$$\frac{h_3}{L} = f_3\left(\frac{H}{L}, \frac{S}{T}, \frac{T}{L}\right). \qquad (12)$$

Considering the effect of H/L, fig. 8 illustrates that values of h_3/L greatly increases when H/L increases up to $H/L \approx 0.15$ after which a slight increase is obtained for $T/L \approx 0.4$. For values of $T/L > 0.4$, a rapid increase arises in values of h_3/L due to increasing H/L up to $H/L \approx 0.10$, beyond which a slight increase occurs.

8. Formulation of the obtained results

About 60% of the resulting values of (q_t/K_sL), $q_f/K_s L$, (q_f/q_t), ($\Delta H/L$) and (h_3/L) resulting due to variation of the main parameters; H/L, S/T and T/L, at random selection were chosen to predict empirical equations. A multi-regression statistical analysis program is applied to the chosen data. Accordingly, different equations, governing the effect of the considered parameters on the seepage characteristics, are obtained as given below. It should be noticed that the predicted equations must be used within the tested ranges of the considered parameters where,

$0 \le H/L \le 0.25$, $0 \le S/T \le 1.0$, and $0 \le T/L \le 1.0$

The obtained equations are given as follows:

The total seepage discharge (q_t)

$$q_t/K_sL = 0.389\,(H/L) - 0.028\,(S/T) + 0.047\,(T/L) - 0.022. \qquad (13)$$

With correlation coefficient, R^2 = 0.992.

The seepage discharge drained by the filter (q_f)

$$q_f/K_sL = 0.11(H/L) - 0.012\,(S/T) + 0.004\,(T/L) - 0.002. \qquad (14)$$

With correlation coefficient, R^2 = 0.912.

The discharge ratio (q_f / q_t)

$$q_f/q_t = 0.813\,(H/L) - 0.118\,(S/T) - 0.227\,(T/L) + 0.24. \qquad (15)$$

With correlation coefficient, R^2 = 0.981.

The loss of head by the cutoff (ΔH)

$$\Delta H/L = 0.552\,(H/L) + 0.07\,(S/T) + 0.043\,(T/L) - 0.061. \qquad (16)$$

With correlation coefficient, R^2 = 0.986.

The height of seepage surface (h_3)

$$h_3/L = 0.059\,(H/L) - 0.015\,(S/T) + 0.009\,(T/L) + 0.01. \qquad (17)$$

With correlation coefficient, R^2 = 0.958.

It should be noted that the predicted equations were checked using the remained 40 % of the data. Verification showed a good agreement with a percentage error about 8%.

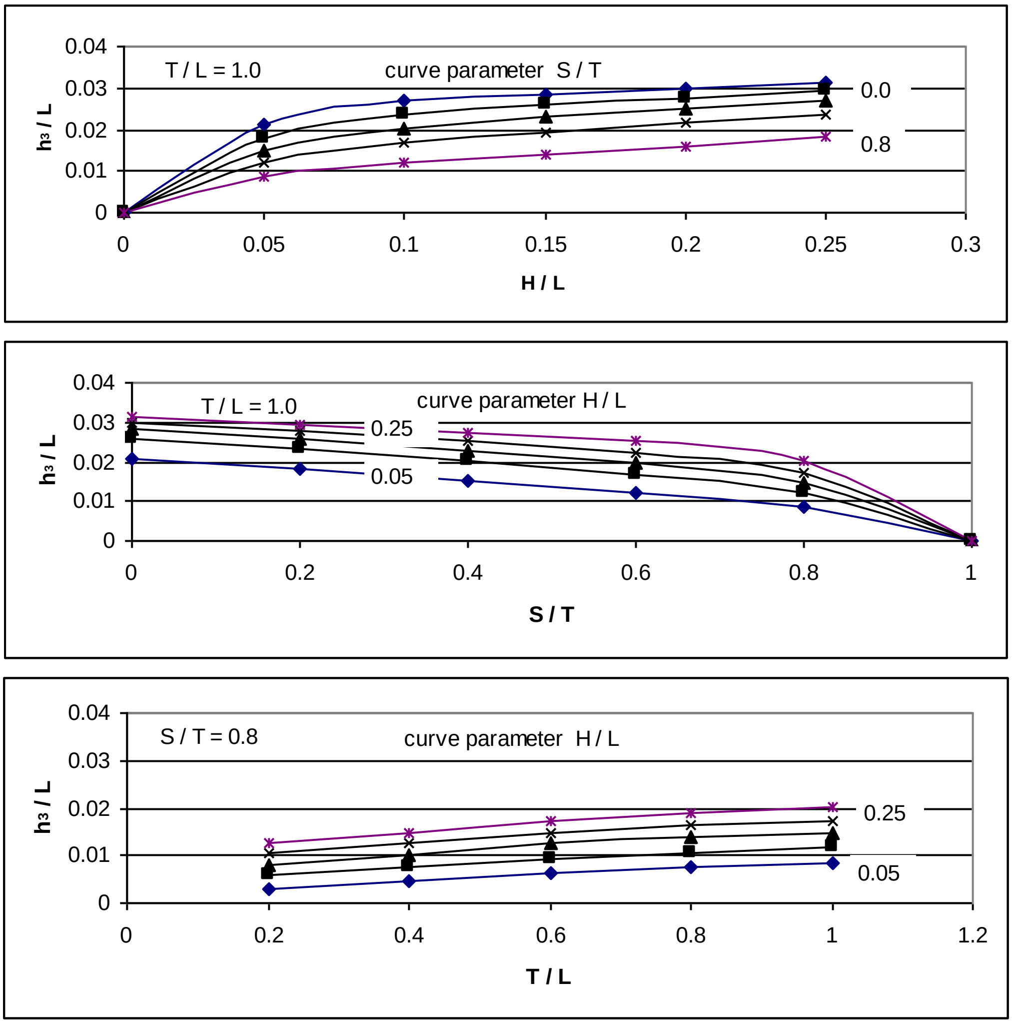

Fig. 8. Effect of the considered parameters on values of h_3/L.

9. Conclusions

In this work problem of seepage through and beneath an earth dam, based on pervious foundation, with cutoff wall, had been studied using numerical model based on the finite element. The main conclusions may be written as follows:

1- Fixing the cutoff wall at the midpoint of dam base is considered the most convenient position.

2- Both the seepage discharge values of total seepage discharge and the seepage discharge entering the filter decreases due to increasing the cutoff wall depth.

3- The loss of head caused by the cutoff wall increases by increasing the acting head, the depth of cutoff and the depth of foundation layer.

4- The height of seepage surface increases due to increasing both of the acting head and the depth of foundation layer While it decreases when the depth of cutoff wall increases.

5- The analysis of the obtained results enabled to develop general equations to determine values of total seepage discharge, the seepage discharge drained by the filter and loss of head by cutoff.

Notations

b Top width of the dam,
H Effective head,

H_d	Dam height,
ΔH	Head loss around the cutoff wall,
h_1	Headwater depth,
h_2	Tail water depth.
h_3	Height of seepage surface,
K_s	Hydraulic conductivity when $K_f = K_d$,
L	Base width of dam,
l	Length of seepage surface,
m_1, m_2	Upstream and downstream slopes, respectively,
q_f	Seepage discharge entering the filter,
q_s	Seepage discharge passing through the pervious layer,
q_t	Total seepage discharge,
S	Depth of cutoff wall, and
T	Depth of permeable foundation layer.

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