COMBINED SEEPAGE BENEATH GRAVITY HYDRAULIC STRUCTURES BASED ON DROPPED BED

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ABSTRACT

Existence of a drop in a stream bed may create a confined seepage followed by an unconfined seepage simultaneously occur in the same field under gravity structures, which is called a combined seepage. The current paper is intended to develop an analytical solution for the problem of combined seepage below gravity hydraulics structures based on pervious layer with a dropped surface. The developed solution can define the maximum height of the free surface and in turn the seepage discharge as well as the location of the free surface once the main parameters are fixed. These parameters are; length of the floor, depth and location of the sheet pile, depth of the foundation layer, horizontal distance between the structure and the drop, head and tail water depths, length of the unconfined zones, drop and height slope. The effect of these parameters, on the seepage discharge and the location of the free surface, is analyzed. The results are formed in the shape of dimensionless design charts. Using such charts, the maximum height of the free surface and the seepage discharge are easily found.

Keywords: Gravity hydraulics structures, Confined seepage, unconfined seepage, Free surface, Design charts

1. INTRODUCTION

Generally, combined seepage occurs under gravity hydraulics structures, while unconfined seepage exists through earthen embankments. Combination of both former types may also take place beneath gravity hydraulics structures constructed on a site of dropped bed line. Hydraulic structures are commonly constructed in streams with a straight bed line. In some cases, site topography may create a drop in the bed resulting two bed lines, the upper and the lower one, as shown in figure (1). Naturally, the structure will be rested in the upper bed at an approaching distance to the drop. Here, the lower bed may dictate the seepage flow to separate from a part of the floor underside. Thus, the seepage field is divided, into two adjacent zones I, II, by a vertical plane passing with the separation point O. Zone (I) is equipped with confined seepage, while zone (II) unconfined seepage occurs, resulting a combined seepage problem. The analytical solution for either confined or unconfined seepage individually cannot be applied to estimate the seepage discharge, but the combination of the two solution, in one solution, will satisfy this purpose, which is the aim of the current study. Estimation of the seepage discharge is a great economic concern, specially, in storage dams since fixe the adequate control measure to reduce the seepage quantity to the required value assigned by the designer. Flat floors practically are not used, therefore the floor should be provided with a sheet pile, close to the heel point of the structure floor as possible, which is considered one of the most effective control measure.
Problems of seepage flow either confined or unconfined, below or through hydraulics structures, had been comprehensively investigated in the previous studies. Various methods and techniques were used to analyze seepage using different approaches, such as analytical, experimental and numerical solutions. Some of the analytical solutions, dealing with confined and unconfined seepage, will be discuss below.
Regarding the confined seepage, Pavolovsky (1922), presented mathematical solutions for some idealized problems of combined seepage beneath flat floors with or without sheet piles, based on pervious layers with finite or infinite depth, to define seepage discharge, distribution of potential along the floor, and distribution of the exit gradient along the exit face of seepage. Khosla et.al (1954), derived formula, expressed by easily used charts, to calculate the potential and the exit gradient. Chugaev (1956) developed the drag coefficient method, in which the seepage field is assumed as pipe and the floor drops or sheet piles act as local resistance. The head loss coefficient for each part is defined to get the total head affecting the seepage. Then, the relative head

loss and the potential along the floor is found, then the seepage discharge and the maximum exit gradient are obtained for any boundary conditions in confined seepage problems. Harr (1962) discussed some analytical solutions for seepage problems presented by Muskat, Pavolovsky, and Kochinee. Chawla and Garg (1969) derived an exact solution to estimate the potential and the exit gradients for hydraulic structure based on pervious layer with infinite inlet and exit faces. Later, Chawla (1972) resolved the same problem but for finite pervious layer.

Considering the unconfined seepage, most of the previous studies are oriented to seepage through earth dams based on pervious or impervious foundation layer. Iterson and Schaffernak (1917), Pavolovsky (1931), Casagrand (1940), Harr (1962), Chugaev (1967), Grishin (1982), and Nedrigy (1983) presented analytical solutions to define; seepage discharge, exit gradient and the location of the free surface through earth dams. A comparison between some of the above solutions revealed that both Casagrand and Grishin solutions nearly give the same results, while Pavolovsky solution gives lower values and both Iterson and Schaffernak solution gives the higher ones of the seepage characteristics, Sasi (2015).

In contrast to the above analytical solutions, for both confined and unconfined seepage, the problem of combined seepage had not been analytically investigated. Only, one experimental study was conducted by Abourohiem (1995) to analyze the combined seepage below gravity hydraulic structures, using the Hele-Shaw model, considering a drop of height one third the depth of the pervious foundation layer. However, results of such study cannot be generalized since based on one specific value of the drop height. Herby, developing an analytical solution for the combined seepage problem is a great importance to be a general solution for estimation the required seepage parameters.

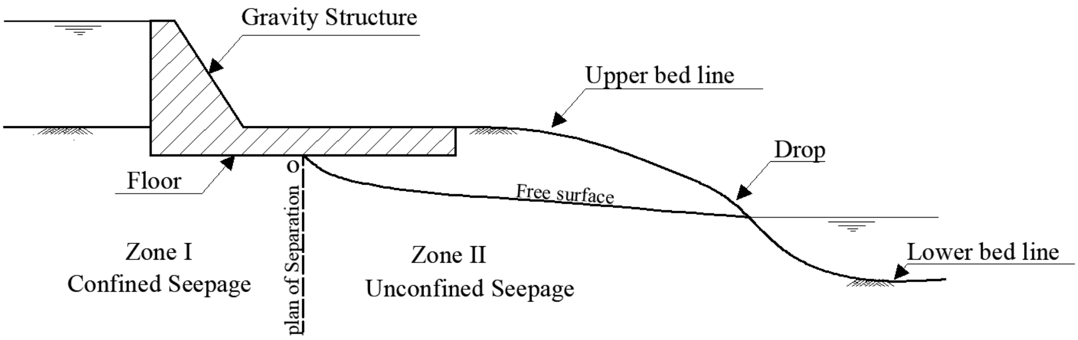

Figure 1. A gravity dam based on dropped bed line

2. DEFINITION OF THE STUDIED PROBLEM

The present study focuses on establishing an analytical solution for the combined seepage problem under a gravity hydraulic structure based on pervious layer of depth (T), as shown in figure (2).

The structure has a floor length (L), and thickness (t), provided by a sheet pile of depth (S) located at a distance (L_1) from its heel point, head and tail water depths (H_1) and (H_2). The structure is located at a distance (X) upstream a drop of height (D), to account for any dissipation works for the flowing water. Occurrence of the bed drop makes the seepage flow to separate from the underside of the floor and the higher part of the sheet pile back. Here, two probable cases of separation may take place, either from the floor only or from both floor and sheet pile, depending the values of H_1, H_2, X and D.

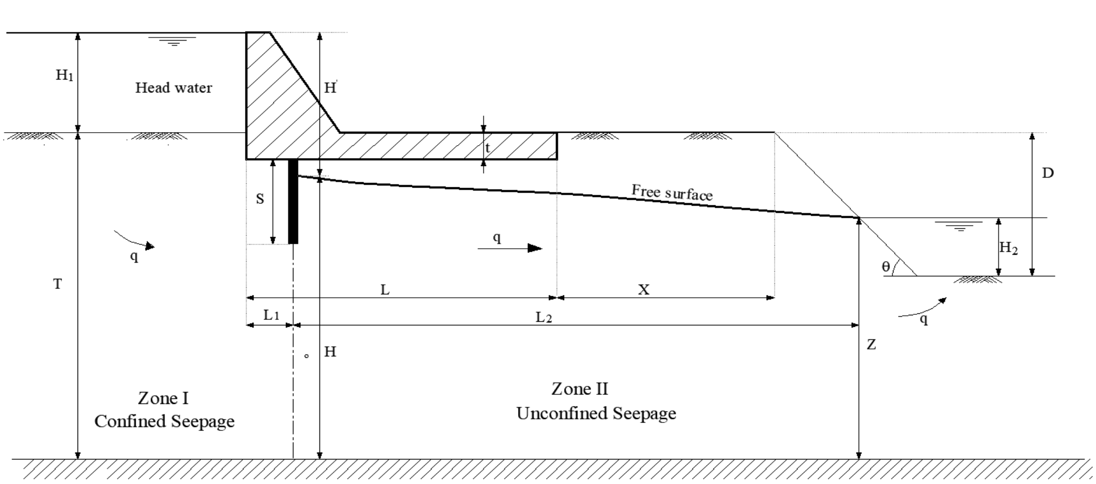

Figure 2. Definition of the combined seepage beneath a hydraulic structure

3. ANALYTICAL STUDY

The combined seepage is a combination of the two basic types of seepage; confined and unconfined. In the present section, the analytical solution of both types will be individually analyzed, hence, the analytical solution for the combined seepage is then developed.

3.1 Confined seepage flow

Considering the analytical solution, for seepage beneath a gravity hydraulic structure, using the complete elliptic integral of the first kind, the unit seepage discharge per a unit width is expressed as,

$$q_{con} = K_s H \frac{K_{(m)}}{2\,K'_{(m)}} \tag{1}$$

where; Ks is the hydraulic conductivity coefficient for the foundation layer, H is the head loss along the confined seepage zone, and K', K are the constants of complete elliptic integral of the first kind. These constants are found on a special tables, Harr (1962) as a function of the modulus (m), where,

$$m = \cos(\frac{\pi}{2}\frac{S}{T})\sqrt{tanh^2\left(\frac{\pi}{2}\frac{L_1}{T}\right) + tan^2\left(\frac{\pi}{2}\frac{S}{T}\right)} \tag{2}$$

From the geometry of the structure, the head H is

$$H = T + H_1 - H_o \tag{3}$$

where; H_o is the maximum height of the free surface, just after the sheet pile.

Substituting for H' in equation (1), yields

$$q_{con} = K_s(T + H_1 - H_o)\frac{K_{(m)}}{2\,K'_{(m)}} \tag{4}$$

3.2 Confined seepage flow

Considering a two dimensional seepage flow on a horizontal boundary satisfying Depuit assumptions in which; free surface has a small inclination, and the hydraulic gradient equals to the slope of the free surface, thus the seepage discharge of the unconfined seepage, q_{unc}, is found as,

$$q_{unc} = \frac{K_s}{2L_2}[H_o{}^2 - Z^2] \tag{5}$$

where; Z is the elevation of the tail water above the impervious layer, then

$$Z = T - D + H_2 \tag{6}$$

Substituting for Z in equation (5), yields

$$q_{unc} = \frac{K_s}{2L_2}[H_o{}^2 - (T - D + H_2)^2] \tag{7}$$

3.3 Combined seepage flow

Considering the steady state condition of the flow, the discharge of both confined and unconfined seepage is the same, then equating the right hand sides (4) and (7), yields

$$H_o{}^2 + 2L_2H_o\frac{K_{(m)}}{2\,K'_{(m)}} = (T - D + H_2)^2 + 2L_2(T + H_1)\frac{K_{(m)}}{2\,K'_{(m)}} \tag{8}$$

Adding the term $\left(L_2\frac{K_{(m)}}{2\,K'_{(m)}}\right)^2$ to each sides of equation (8) and simplifying, one get

$$\frac{H_o}{T} = \sqrt{\left(1 - \frac{D}{T} + \frac{H_2}{T}\right)^2 + 2\frac{L_2}{T}\left(1 + \frac{H_1}{T}\right)\frac{K_{(m)}}{2\,K'_{(m)}} + \left(\frac{L_2}{T}.\frac{K_{(m)}}{2\,K'_{(m)}}\right)^2} - \left(\frac{L_2}{T}.\frac{K_{(m)}}{2\,K'_{(m)}}\right), \tag{9}$$

where; L_2 is the length of the zone of unconfined seepage, since

$$L_2 = L - L_1 + X + M(D - H_2), \tag{10}$$

where; $M = \cot(\theta)$, and θ is the angle of drop inclination, then

$$\frac{L_2}{T} = \frac{L}{T} - \frac{L_1}{T} + \frac{X}{T} + M\left(\frac{D}{T} - \frac{H_2}{T}\right) \tag{11}$$

Once the maximum height of the free surface (H_o) is found from equation (9), the quantity of seepage discharge is then obtained using equation (4) or equation (7). Thus, the relative seepage discharge q/K_sT, is defined as,

$$\frac{q}{K_s\,T} = \left(1 + \frac{H_1}{T} - \frac{H_o}{T}\right)\frac{K_{(m)}}{2\,K'_{(m)}} \tag{12}$$

The height of the free surface h_x at any fractional distance (x) measured from the sheet pile is

$$h_x = \sqrt{{H_o}^2 - \frac{2\,q}{K_s}(x)} \tag{13}$$

4. MAIN PARAMETERS AFFECTING THE COMBINED SEEPAGE

Considering a hydraulic structure with fixed dimensions for the floor length (L) and sheet pile location (L_1), and based on the experimental study conducted by Abourohiem (1995), the main parameters that affect the characteristics of the combined seepage are; the approaching distance (X), height of drop (D), depth of the sheet pile (S), and both head and tail water depths (H_1) and (H_2). As for the length L_2, it is function of L_1, L, X, D, and H_2 as given in equation (10). Calculations revealed that the slope factor M a slight effect.

Such main parameters, representing the input data, could be correlated with the seepage characteristics; seepage discharge q, and maximum height of free surface H_o, as output data in a dimensionless form. Considering the pervious layer depth (T) as a reference parameter, both input and output data may be expressed as;

$$\frac{H_o}{T} = f_1\left(\frac{X}{T} + \frac{S}{T} + \frac{D}{T} + \frac{H_1}{T} + \frac{H_2}{T}\right), \text{and} \tag{14}$$

$$\frac{q}{K_s\,T} = f_2\left(\frac{X}{T} + \frac{S}{T} + \frac{D}{T} + \frac{H_1}{T} + \frac{H_2}{T}\right) \tag{15}$$

5. DESIGN CHARTS

It is worthy to notice that representing the relative values of seepage discharge q/K_sT, and the relative maximum height of the free surface H_o/T as a function of all the independent parameters on the same graph is very helpful tool for the design purposes. The coaxial method of graphical Correlation, Linsely (1975), and the computer statistical facilities are used to construct such graphs, as presented in figures (3) through (8).

Figures (3, 4, and 5) present in graphical form for the calculated values of the maximum height of the free surface H_o/T as a function of the relative height of drop (D/T), the relative depth of the sheet pile (S/L), the relative height of drop (H_1/T), and the relative tail water depth (H_2/T) for different values of the relative approaching distance (X/T = 0.0, 0.5, and 1.0), respectively. On the other hand, values of the seepage discharge q/K_sT are graphically presented in figures (6, 7, and 8), as a function of the above relative values; D/T, S/L, H_1/T, H_2/T and X/T.

6. DESIGN EXAMPLE

An example to illustrate the use of the presented design charts is given here. Let a hydraulic structure of floor length L = 30 m, *foundation* depth T = 20 m, drop height D= 10 m, approaching distance X = 20 m, sheet pile depth S = 5 m, head and tail water depths H_1= H_2 = 2 m. Then, D/T=0.50, X/T=1.0, S/T=0.20, H1/T= H_1/T = 0.10. Using these relative values in figures (4, 7), $H_o \approx$ 19.56 m, $q/K_s \approx$ 3.6 m.

7. CONCLUSIONS

An Analytical solution for the problem of combined seepage, under gravity hydraulics structures with sheet pile based on pervious layer with a drop surface is obtained.

Two equations are developed in a dimensionless form, for estimating both maximum height of the free surface, H_o/T and seepage discharge, q/K_sT. Such equations are graphically expressed in the form of design charts to easily define the values of above seepage parameters H_o and q.

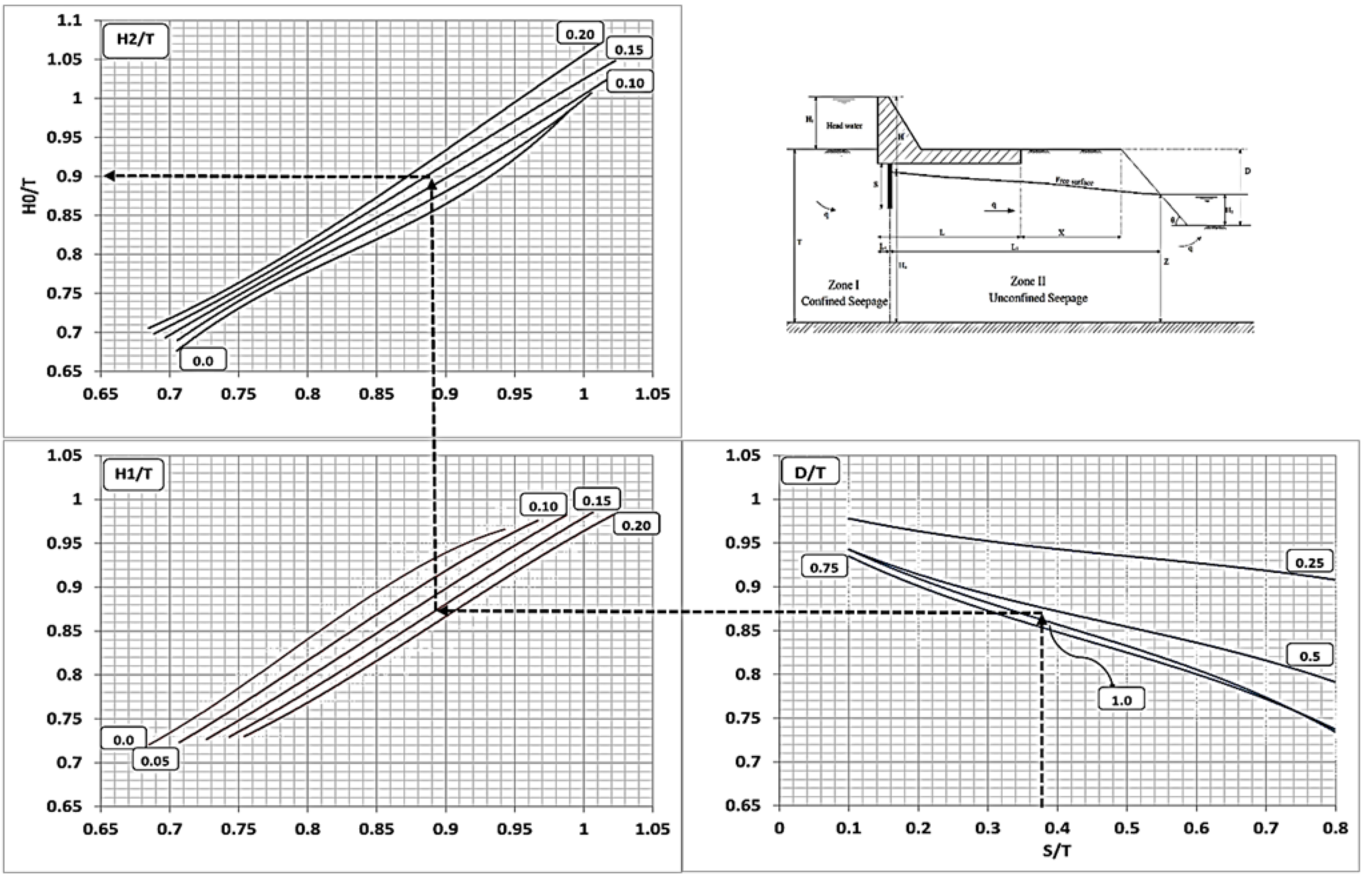

Figure 3. The maximum height of the free surface H_o/T for X/T = 0.0

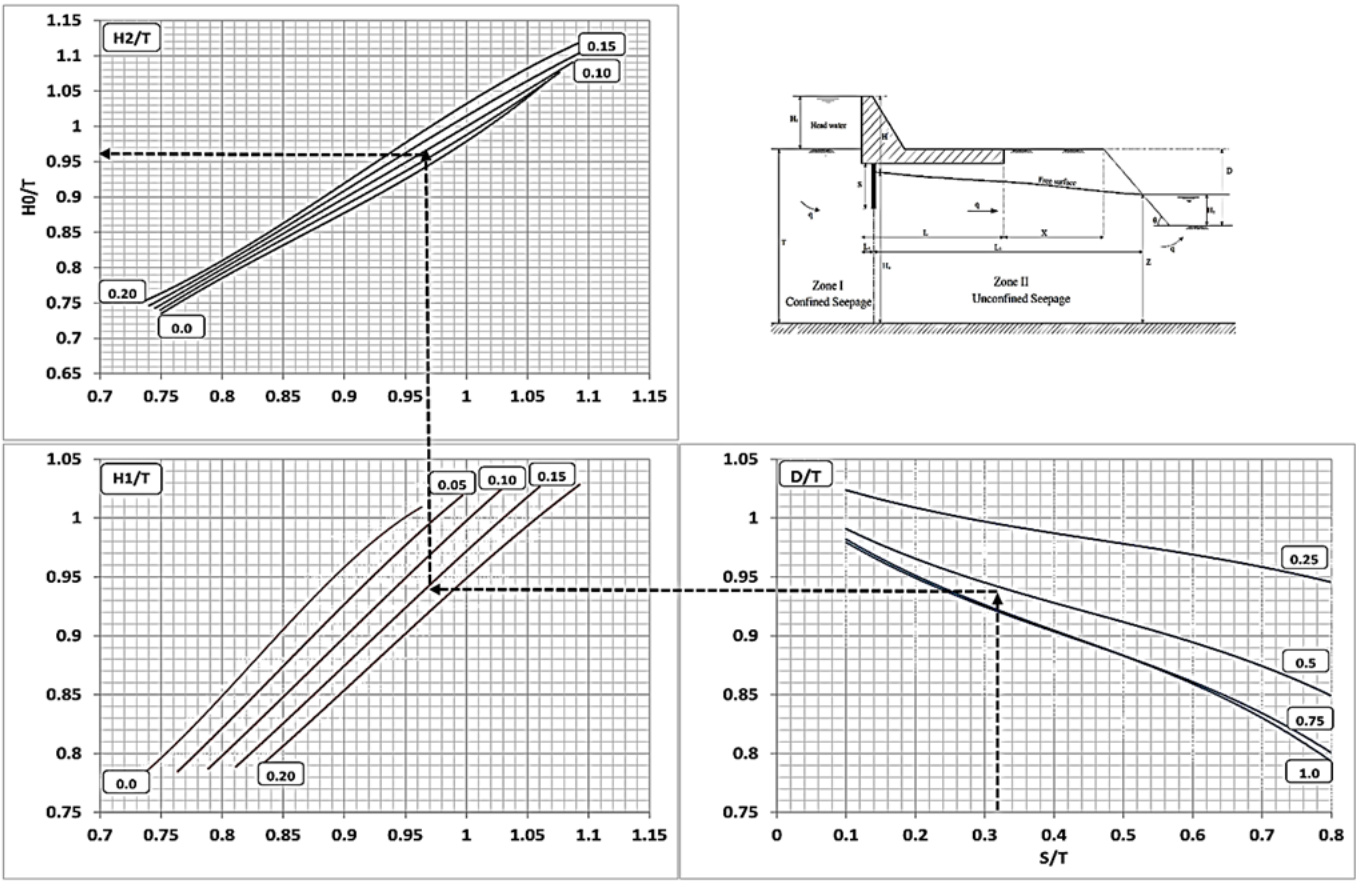

Figure 4. The maximum height of the free surface H_o/T for X/T = 0.50

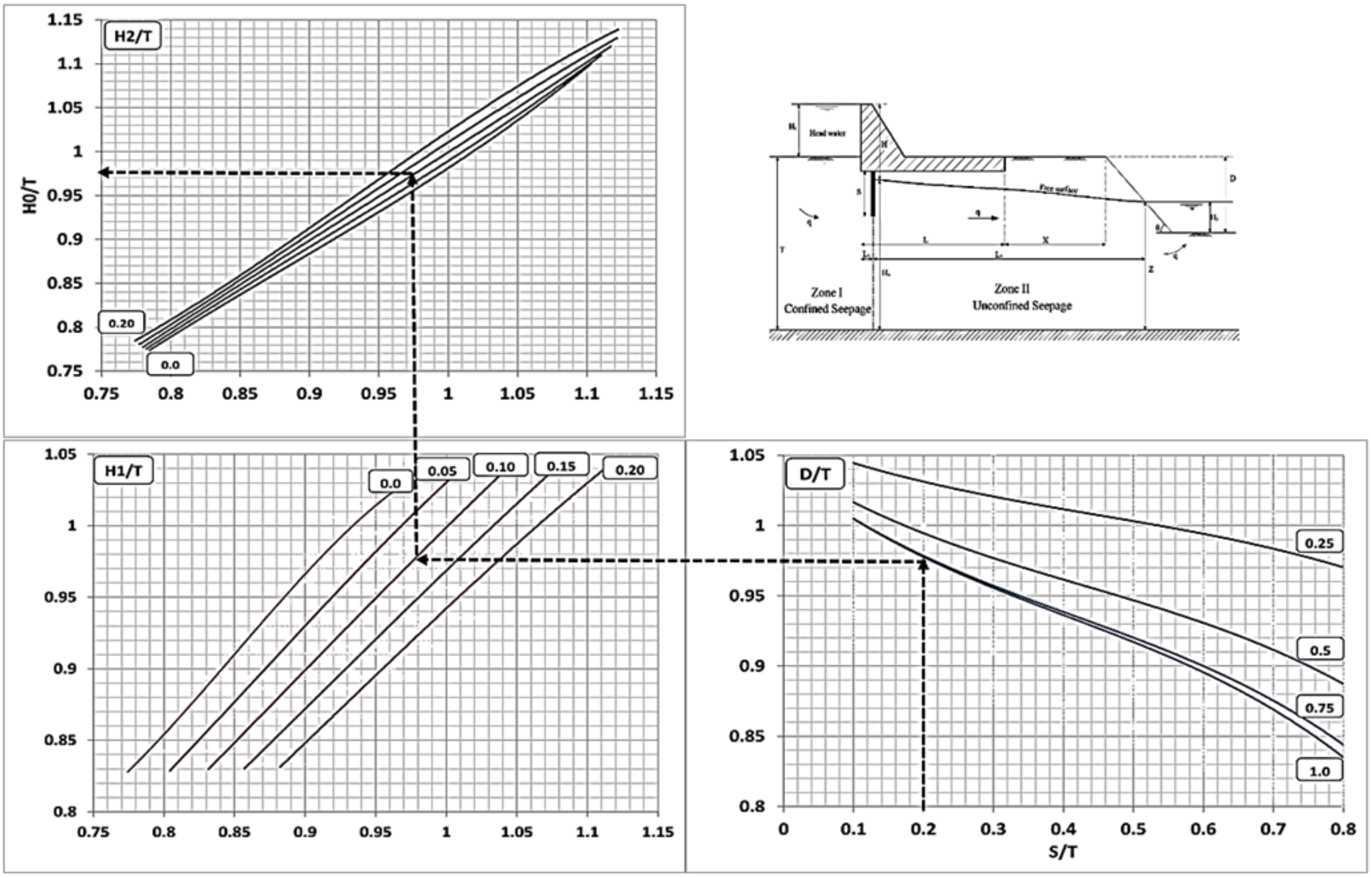

Figure 5. The maximum height of the free surface H_o/T for X/T = 1.0

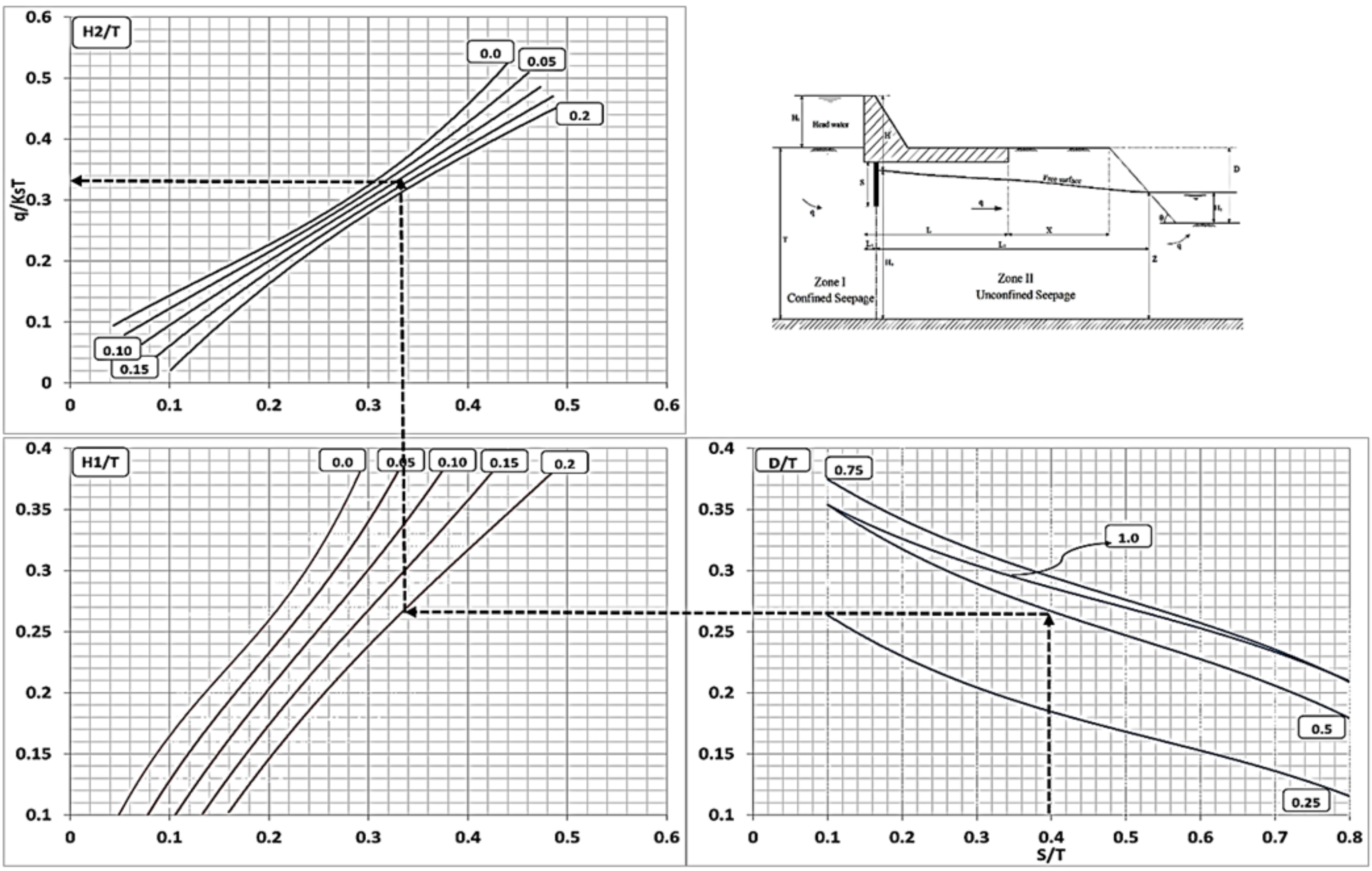

Figure 6. The relative values of seepage discharge q/K_sT for X/T = 0.0

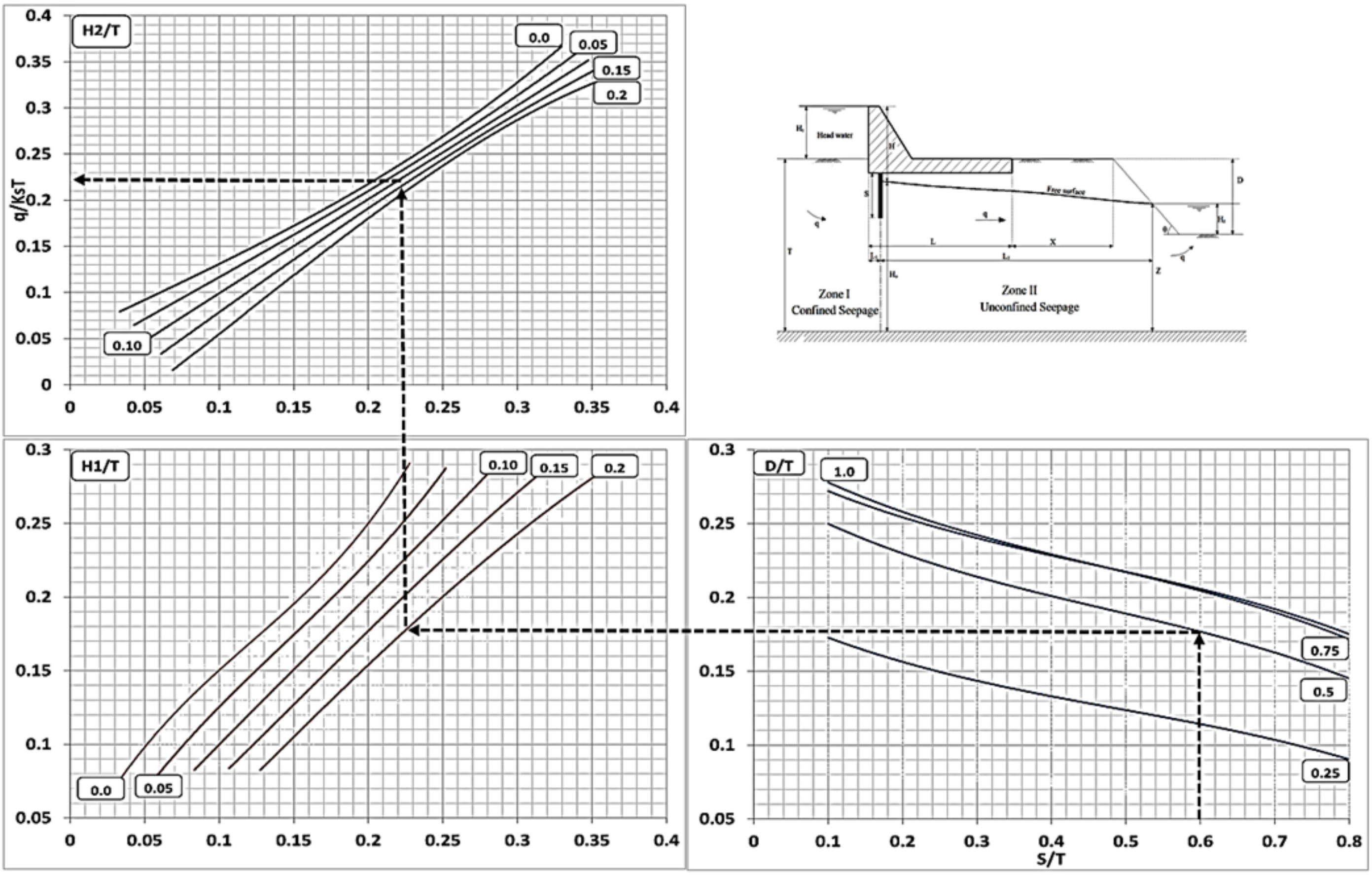

Figure 7. The relative values of seepage discharge q/K_sT for X/T = 0.50

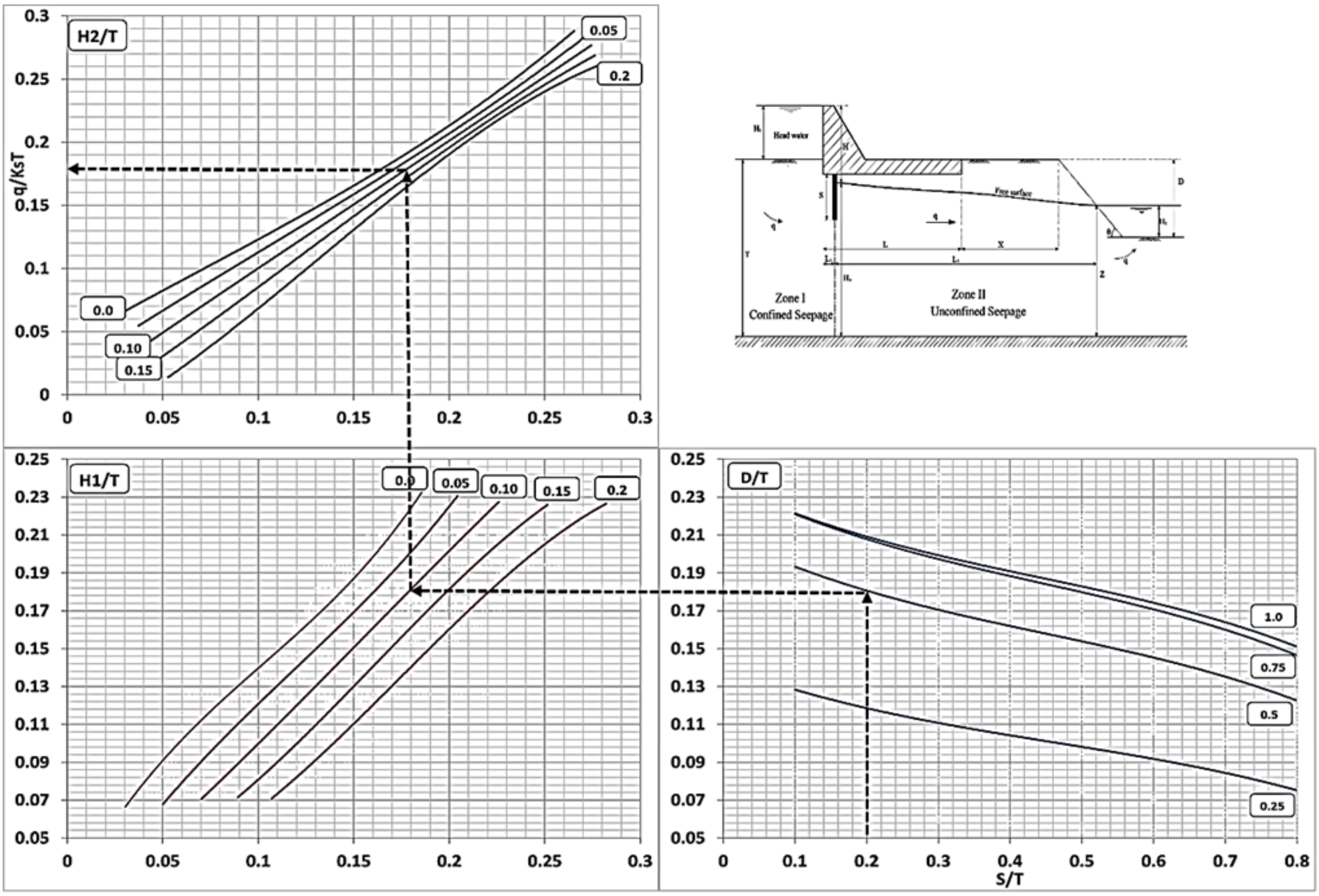

Figure 8. The relative values of seepage discharge q/K_sT for X/T = 1.0

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