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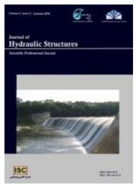

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Numerical study concerning the different drainage systems in earth dams

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Abstract

One of the most popular tools for dealing with the seepage problem in embankment dams is using different types and shapes of downstream drains. So, the paper presents a comprehensive study of the different drainage systems through such dams. Many earth dam models are investigated through the SEEP/W model representing different dimensions and geometry of downstream drains. A comparison is carried out between the present study and previous experimental and numerical studies and the results of the present study are almost close to the previous studies. The present work concludes that the most influential factor in a horizontal drain is the length, and the thickness has a negligible effect. The reasonable length ratio of a horizontal drain (L/B) is about 0.34 according to the minimum seepage. The angle of toe drains has a slight effect on the different seepage parameters. The performance of the inclined chimney drain is better than the vertical drain to control the seepage.

Keywords: Earth dams, Seepage control, Drainage systems, SEEP/W.

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1. Introduction

Earth embankment dams are widely built in water streams and rivers and are generally economical compared with other dams. Embankment dams represent about 70% of dams in the world [1]. Seepage is one of the most serious stability concerns of embankment dams. The most popular reasons for embankment dam collapse are overtopping and seepage [2]. It was found that about 35% of dams' failures all over the world were due to seepage [3]. The main two problems of seepage through embankment dams are; the amount of seeped water which is of great importance for storage dams, in addition to the stability of the earth dam against seepage [4]. Many precautions have been studied for controlling seepage and avoiding or preventing such failure. Using different drainage systems and cores, grout curtain have been the main methods studied for seepage control through or beneath earth dams.

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Elmasry and Saafan [5] studied the seepage flow in embankment dams with pipe drains. The maximum effect of the pipe location was obtained at 0.3 to 0.5 of the dam's bottom width measured from the downstream side. Elmasry [6] studied the seepage flow in embankment dams using a chimney drain. The maximum effect on the exit gradient was obtained when the distance between the drain and the upstream side of the dam was two times the upstream water head. Abdel-Gawad and Shamaa [7] investigated the seepage through earth dams with horizontal drains founded on impervious soil. Different parameters such as the upstream slope and position of the drain were investigated and the numerical results had good agreement with the analytical results. Abdel-Gawad [8] presented some equations to solve the seepage problem through earth dams depending on a previous work [7] and the average relative error was less than 5%.

Djehiche et al. [9] carried out an experimental study of seepage through a homogenous earth dam. Empirical relations were obtained to control the seepage flow through chimney drains of earth dams. Giglou and Zeraatparvar [10] investigated different parameters of earth dams such as permeability coefficient and side slopes to analyze the seepage problem. Some equations were presented to determine the total seepage amount through homogeneous earth dams. Giglou et al. [11] studied the seepage through homogeneous and non-homogeneous embankment dams. A relation was presented to estimate the seepage discharge through a homogeneous earth dam with a vertical drain. Moharrami et al. [12] investigated the influence of using horizontal drains with different numbers, lengths, and locations at the upstream zone of the embankment dam on the stability of the upstream face at the rapid drawdown state.

Salmasi and Mansuri [13] studied the effect of upstream and downstream side slopes, dimensions of horizontal drains, and the ratio between horizontal and vertical permeability coefficients on the seepage flow through homogeneous earthen dams. Salmasi et al. [14] carried out a numerical investigation on the influence of using relief wells in the downstream area of embankment dams. Aboelela [4] studied the seepage flow in embankment dams with different toe drains. The used drainage systems showed a significant effect on the seepage flow through earth dams resting on pervious soil. Irzooki [15] studied the seepage flow through homogenous earth dams with horizontal drains using the SEEP/W numerical model. The seepage discharge increased with the increase in the horizontal drain's length.

Nourani et al. [16] used the SEEP/W numerical model to simulate the effect of pipe drains on the uplift pressure under concrete gravity dams. Abbas [17] computed the seepage quantity in embankment dams using a toe drain. The seepage discharge decreased with increasing the angle of the toe drain. Also, it was concluded that the seepage quantity increased by increasing the length of the toe drain. Sazzad and Rahman [18] investigated the effect of vertical and inclined chimney drains on the seepage line, pore pressure, and flow rate in earth dams. The results showed that the earth dam with vertical or inclined chimney drains at the downstream side decreased the seepage line level through the earth dam. Also, the pore pressure was minimum in the downstream vertical chimney drain case. Salmasi and Nouri [19] demonstrated that the use of an upstream impermeable blanket can effectively enhance the dam's stability against seepage.

Norouzi et al. [20] studied the influence of the impermeable core and cut-off wall on the seepage flow through and beneath the Sabalan embankment dam in Iran. Salmasi et al. [21] introduced some recommendations for the use of cut-off walls and downstream drains in embankment dams. Alam [22] evaluated the seepage flow in embankment dams using different drains. The results illustrated that the pore pressure was reduced through a linear relationship with distance with the chimney drain, while the discharge was high in the case of the horizontal drain. Mostafa and Shen [23] studied the seepage in embankment dams with different permeability coefficients. Decreasing the permeability coefficient caused a noticeable reduction in the seepage flow in the embankment dam.

Refaiy et al. [24] investigated the influence of the geometry of downstream drains on seepage in homogeneous dams resting on impervious soil. The results showed that the most important variable of the drain was the length, and the thickness and inclination angle had a negligible effect. Kumar et al. [25] studied the seepage in an embankment dam on impermeable soil with a horizontal drain. It was found that increasing the length of the drain increased the flow rate. Abd et al. [26] introduced a simplified formula to compute the seeped water quantity in homogeneous embankment dams with toe drains. Mostafa and Shen [27] investigated the influence of the thickness and upstream and downstream slopes of the dam zones on the seepage flow in the embankment body. The present study aims to investigate the effects of the different downstream drains such as horizontal, toe, combined, and chimney drains on the seepage flow in embankment dams and introduce some comparisons between these different drainage systems. Determining the optimum horizontal drain length according to the minimum seepage has not been investigated widely as illustrated from the previous research.

2. Dimensional analysis

The general equation of the different parameters is illustrated as:

$$f(\rho, g, b, B, h, H, q, k, k_d, L, t, \beta) = 0 \tag{1}$$

Where:

ρ: density of water, g: gravitational acceleration, b: top width of the dam, B: bottom width of the dam, h: upstream head on the earth dam, H: total height of the earth dam, k: hydraulic conductivity of the dam, k_d: hydraulic conductivity of the drain, L: length of the drain, q: seepage discharge rate per unit length, t: thickness of the drain, and β: inclination angle of the drain.

By using Buckingham's π method, assuming the density of water and gravitational acceleration to be constant parameters, the general equation is given as:

$$f\left(\frac{b}{h}, \frac{B}{h}, \frac{H}{h}, \frac{q}{kh}, \frac{k_d}{k}, \frac{L}{h}, \frac{t}{h}, \beta\right) = 0 \tag{2}$$

By taking the different dam's dimensions, upstream level, and hydraulic conductivity as constant parameters, the relationship between the variables is written as:

$$f\left(\frac{q}{kh}, \frac{L}{B}, \frac{t}{h}, \beta\right) = 0 \tag{3}$$

3. Materials and methods

The main goal of this study is to present a comprehensive investigation of the different seepage drains through earth dams. The SEEP/W model [28] is applied in this study for modelling and analysing the different drainage systems. The SEEP/W simulates the water flow in different earthworks such as earth dams. It depends on the seepage in saturated or unsaturated zones depending on Darcy's equation. It is used to investigate the water flow in steady and transient conditions. It is used in the study due to the good results from many previous seepage studies, and it was verified by different previous field and experimental results. The governing formula is shown as:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+Q=\frac{\partial \theta}{\partial t} \quad (4)$$

Where:
h: total water head (m).
k_x: permeability coefficient in the horizontal direction (m/sec).
k_y: permeability coefficient in the vertical direction (m/sec).
Q: applied discharge (m^3/sec per unit volume).
θ: volumetric water content (m^3 per unit volume).
t: time (sec).

The SEEP/W main inputs include sketching the cross-section, defining the material properties, and assigning the boundary conditions. The total head boundary condition is selected for the upstream face, and the zero head state is assigned to the drain. The quads and triangles meshing is applied for the numerical models. The elements and nodes of the numerical model are 2029 and 2168. The SEEP/W determines the seeped water quantity, draws the seepage lines, and obtains the seepage characteristics such as the pore pressure, velocity, and hydraulic slope. For the numerical model, a homogeneous dam is selected with a total height of 25 meters, 5 meters freeboard, 7 meters crest width, and dry downstream condition. The side slopes of the homogeneous earth dam are stable depending on the review [3]. The dimensions of the dam are calculated depending on the recommendations of the U.S. Bureau of Reclamation [29] as shown in Figure 1.

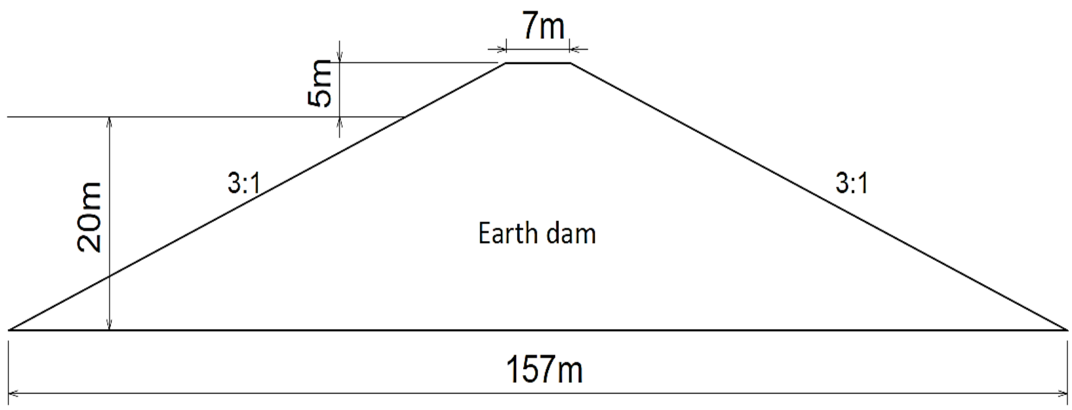


Figure 1. Geometry of the homogeneous earth dam

The Different hydraulic parameters of the earth dam and drains are selected according to the literature recommendations and illustrated in Table 1 and the same material is used in the different drainage systems for accurate comparisons. Various dimensions and geometry of seepage drains are studied such as horizontal, toe, combined, and chimney drains as illustrated in Figure 2.

Table 1. Properties of the used materials in the different zones

Element	Material	Hydraulic conductivity (k)
Dam body	Silt	$1*10^{-6}$ m/sec
Horizontal, toe, combined, and chimney drains	Gravel	$1*10^{-2}$ m/sec

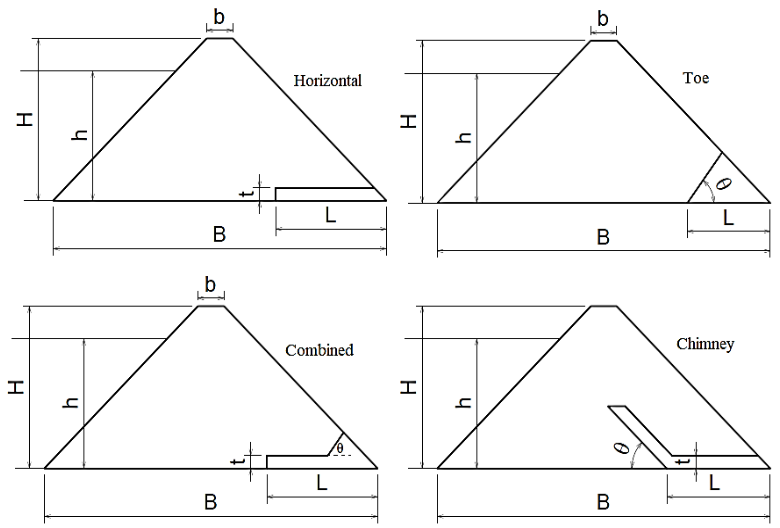


Figure 2. Different drainage systems of the earth dam

The study introduces a comparison between the different seepage drains and the parameters under study are summarized, and tabulated in Table 2.

Table 1. Methodology of different drainage models and parameters under study

Horizontal	Toe	Combined	Chimney
Effect of drain's length: L/B= 0.125,0.25, 0.375, 0.5 Effect of drain's thickness: t/h=2.5,5,7.5,10%	Comparison between vertical and inclined toe drains	Comparison between the horizontal, toe, and combined drains	Comparison between the vertical and inclined chimney drains

4. Verification of the numerical model

In this section, a comparison is carried out between the obtained results using SEEP/W model and the experimental and numerical investigations using SEEP2D numerical model by Refaiy et al. [24] who studied the influence of the geometry of downstream drain on seepage in homogeneous dams as shown in Figure 3.

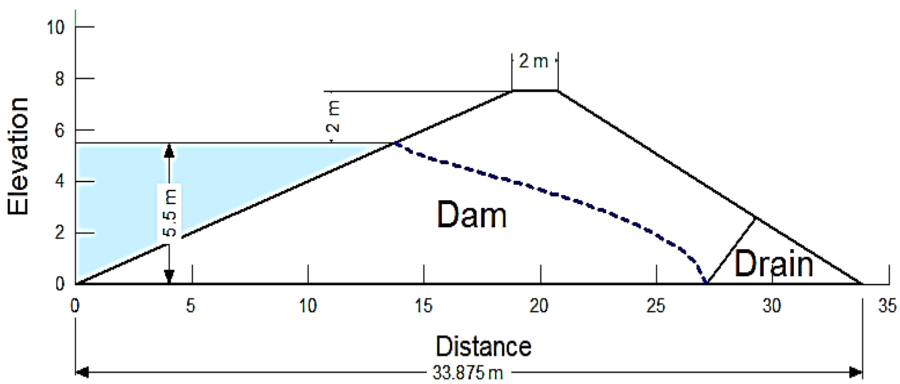
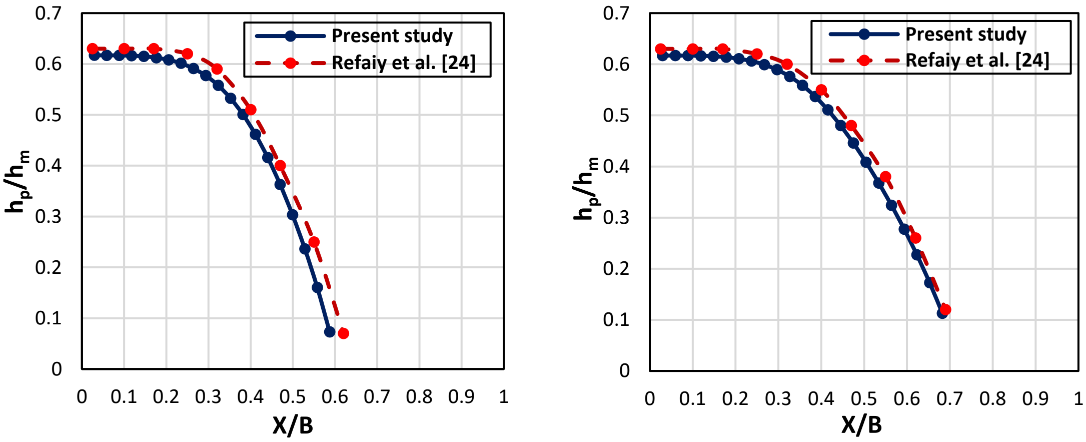


Figure 3. Definition sketch for a homogenous earth dam with a toe drain [24]

Figure 4 illustrates the relative pore pressure (h_p/h_m) at different distances (X/B) for horizontal and toe drains with drain's length ratios (L/B) equal to 0.32 and 0.2 respectively. It is clear that for the two cases, there is a good agreement between the obtained results of the present work and previous results by Refaiy et al. [24]. Also, the values of the discharge coefficient (q/kh_m) in the two cases are shown in Figure 5, from which the present and previous results are almost close to each other.

Where: h_p: pressure head, h_m: maximum head on the upstream side of the dam, X: distance from the beginning of the dam (heel), B: bottom width of the dam, L: length of the drain, q: seepage discharge rate per unit length, and k: hydraulic conductivity of the dam.



a) Horizontal drain b) Toe drain

Figure 4. Relative pore pressure (h_p/h_m) at different distances (X/B) for different cases

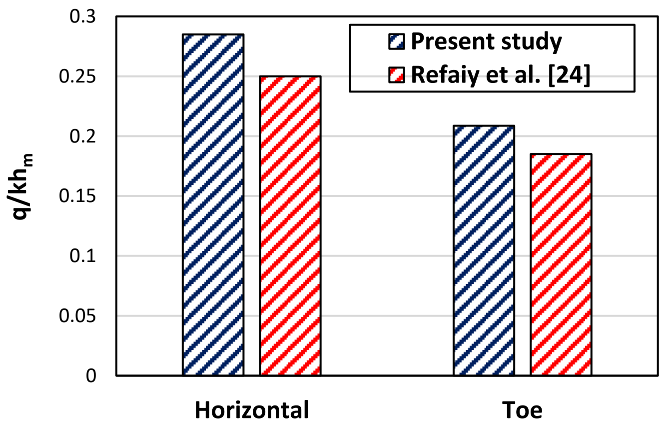


Figure 5. Seepage discharges values (q/kh_m) of horizontal and toe drains for different studies

5. Results and discussion
5.1. Horizontal drains

To investigate the influence of the dimensions of the horizontal drain on the seepage properties in embankment dams, different numerical models are carried out representing different length and thickness ratios. Four numerical models are carried out with different drain's length ratios (L/B) ranging from 0.125 to 0.5, in addition to four models with drain's thickness ratio (t/h) ranging from 2.5 to 10%.

Figure 6-a shows the relation between the relative horizontal drain's length (L/B) and the discharge coefficient (q/kh), from which it is clear that increasing the relative length causes a significant increase in the seeped water quantity (about 204%). This is because of the shorter path needed by the flow to contact the first point of the drain that increases the seepage amount. The relation between the base distance and the pore pressure is shown in Figure 6-b for different relative drain's lengths. The chart illustrates that the pore pressure is reduced with the increase in the relative drain's length. This is because of decreasing the path needed by the flow to contact the drain which deviates the seepage surface away from the downstream face of the earth dam.

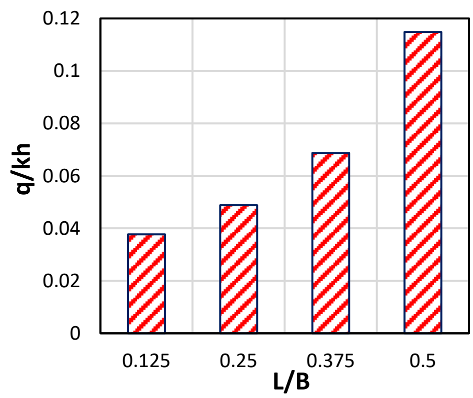


Figure 6-a. Relation between the relative horizontal drain's length (L/B) and the discharge coefficient (q/kh)

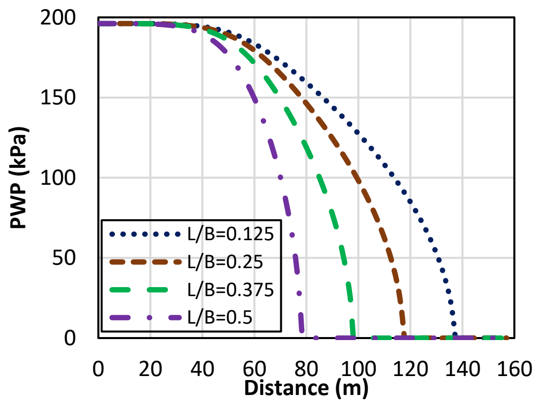


Figure 6-b. Relation between the base distance and the pore pressure (PWP) for different (L/B)

The relation between the relative horizontal drain's length (L/B) and the maximum water velocity (v) through the dam body is shown in Figure 6-c. It can be seen that increasing the relative length increases the water velocity (by about 72%). Figure 6-d shows the relation between the base distance and the hydraulic slope (i) for different relative drain's lengths. From the figure, the gradient increases by increasing the relative drain's length (by about 70%), as increasing the drain's length causes a decrease in the water path from the upstream side slope to the drain which makes the hydraulic slope steeper.

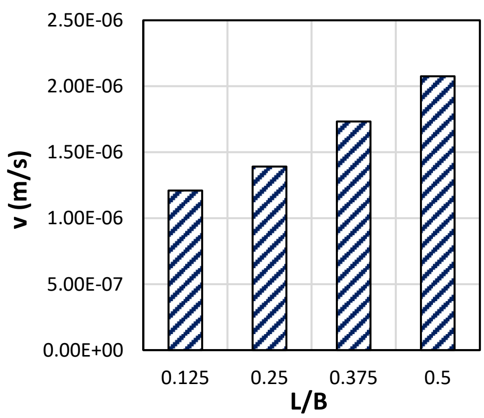


Figure 6-c. Relation between the relative horizontal drain's length (L/B) and the water velocity (v)

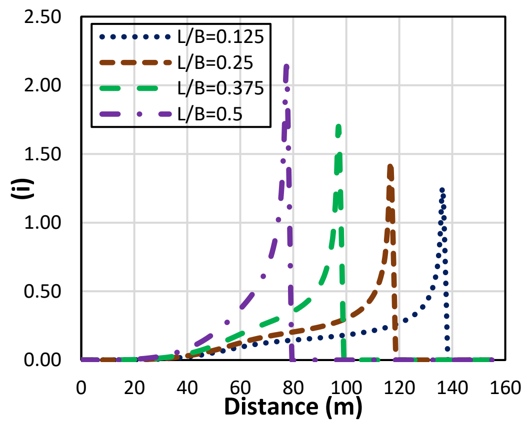


Figure 6-d. Relation between the base distance and the hydraulic slope (i) for different (L/B)

It is seen that increasing the length increases the seeped water quantity while it causes a reduction in the pore pressure through the earth dam. Also, the rate of increasing the different seepage parameters, especially the discharge, is very high at a relative length of 0.5. So, the reasonable relative length should be from 0.25 to 0.38 approximately. To confirm this result, Figure 7 shows the relation between the percentage of decreasing the seepage discharge and the remaining pore pressure at the centre line of the dam with the different length ratios. From the figure, it can be noticed that the two curves representing the seepage discharge and the pore water pressure, intersect at a relative length of 0.34. Then, the optimum relative length is about 0.34 according to the minimum seepage parameters.

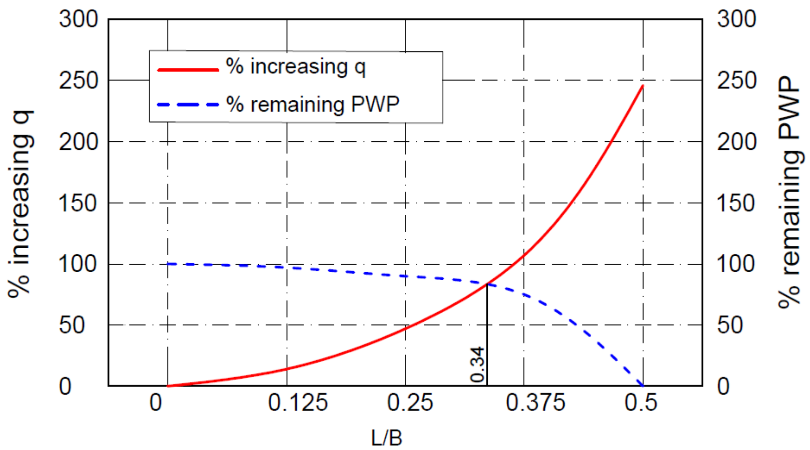


Figure 7. Relation between the percentage of decreasing the seeped water quantity, the remaining pore pressure, and the different length ratios (L/B)

Figure 8-a illustrates the relation between the relative horizontal drain's thickness (t/h) and the discharge coefficient (q/kh), from which it is seen that increasing the relative thickness has a negligible effect on the seeped water quantity. The relation between the base distance and the pore pressure is illustrated in Figure 8-b for different relative drain's thicknesses. The chart illustrates that the pore pressure is reduced slightly by increasing the relative drain's thickness.

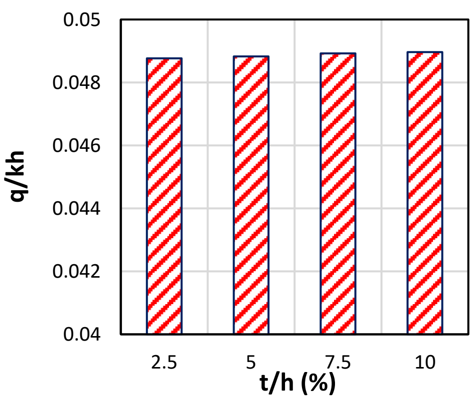


Figure 8-a. Relation between the relative horizontal drain's thickness (t/h) and the discharge coefficient (q/kh)

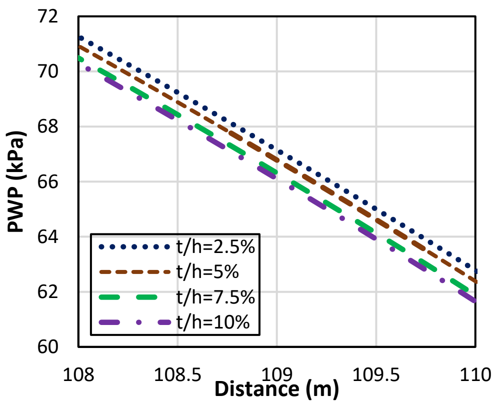


Figure 8-b. Relation between the base distance and the pore pressure (PWP) for different (t/h)

The relation between the relative horizontal drain's thickness (t/h) and the maximum water velocity (v) through the dam body is shown in Figure 8-c. It can be noticed that increasing the relative drain's thickness causes a small reduction in the water velocity (by about 8%). Figure 8-d illustrates the relation between the base distance and the hydraulic slope (i) for different relative drain's thicknesses, from which a small reduction in the slope is obtained by increasing the relative drain's thickness (with about 8%).

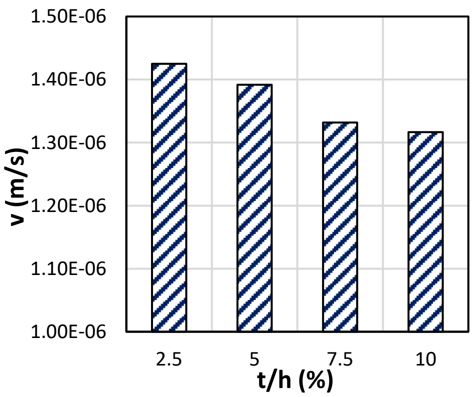


Figure 8-c. Relation between the relative horizontal drain's thickness (t/h) and the water velocity (v)

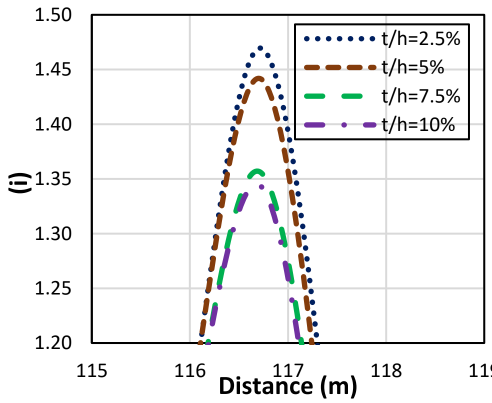


Figure 8-d. Relation between the base distance and the hydraulic slope (i) for different (t/h)

5.2. Toe drains

The influence of the toe drain's angle on the different seepage properties is studied by comparing the performance of the vertical and inclined toe drains with the same horizontal length (L/B = 0.125). So, two models are studied using a vertical toe drain and a 45° inclined one. Figure 9-a illustrates the relation between the two toe drains and the discharge coefficient (q/kh), from which it is noticed that the seeped water quantity is almost the same in the inclined and vertical toe drains. The relation between the base distance and the pore pressure for the two toe drains is shown in Figure 9-b. It is seen that there is no noticeable difference in the pore pressure between the two toe drains.

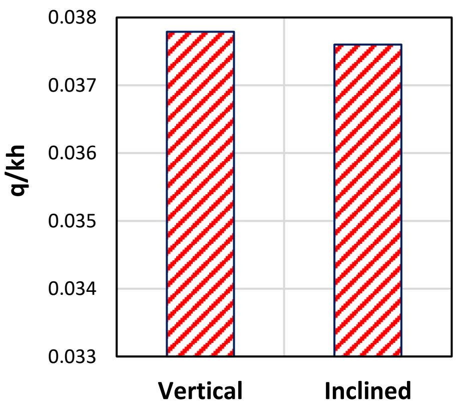


Figure 9-a. Relation between different toe drains and the discharge coefficient (q/kh)

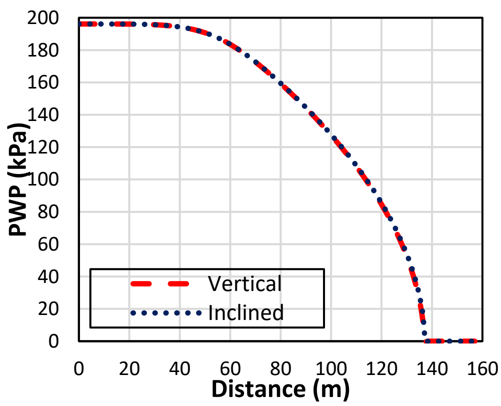


Figure 9-b. Relation between the base distance and the pore pressure (PWP) for the two toe drains

Figure 9-c shows the relation between the two toe drains and the water velocity (v). The chart shows that the water velocity in the vertical toe drain is slightly higher than that in the inclined one (by about 13%). The relation between the base distance and the hydraulic slope (i) for the two toe drains is shown in Figure 9-d. It is noticed that the gradient is higher in the vertical drain compared to the inclined toe drain (with about 12%), as the vertical toe drain causes more sudden change in the seepage line which increases the hydraulic gradient.

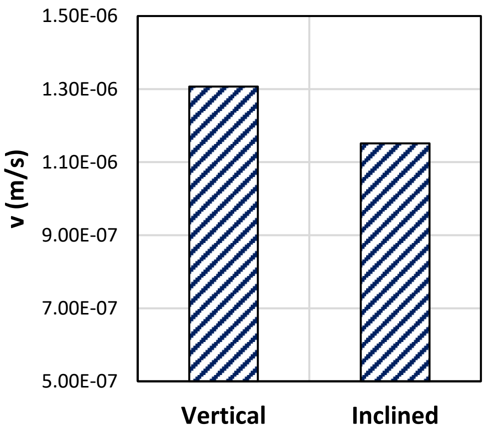


Figure 9-c. Relation between different toe drains and the water velocity (v)

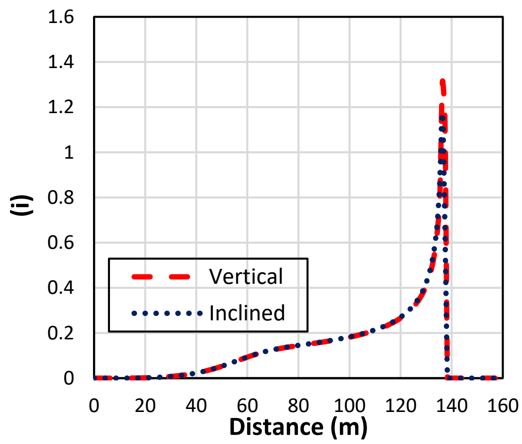


Figure 9-d. Relation between the base distance and the hydraulic slope (i) for the two toe drains

5.3. Combined drains

A combination of horizontal and inclined toe drains is investigated for a comparison between the effects of the horizontal, toe, and combined drains on the different seepage parameters. The horizontal and combined drains have the same length (L/B = 0.25), while the toe drain has a relative length equal to 0.125. Figure 10-a shows the relation between different types of drains and the discharge coefficient (q/kh), from which it can be concluded that the seeped water quantity is higher in the case of horizontal and combined drains compared to the toe drain (by 30%). This is because of the short path needed by the seeped water to contact the downstream drain which increases the seeped water quantity. No remarkable difference is obtained between the horizontal and combined drains. The relation between the base distance and the pore pressure for different drains is shown in Figure 10-b. It is seen that using horizontal or combined drains reduces the pore pressure compared to the toe drain. This is because of decreasing the path needed by the water to contact the drain which increases the distance between the phreatic line and the downstream side.

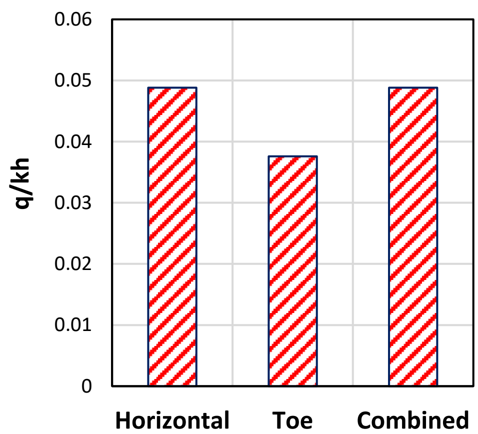


Figure 10-a. Relation between different types of drains and the discharge coefficient (q/kh)

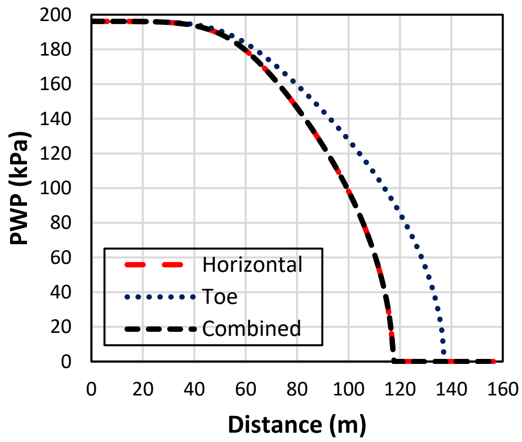


Figure 10-b. Relation between the base distance and the pore pressure for downstream drains

Figure 10-c illustrates the relation between different types of drains and the water velocity (v). It can be noticed that the velocity in the toe drain is lower than that in horizontal or combined drains (with 21%). The relation between the base distance and the hydraulic slope (i) for different drains is illustrated in Figure 10-d. It is concluded that the gradient is lower in the toe drain compared to other drains (by 22%), as decreasing the distance between the dam's upstream side and the drain causes a steep gradient.

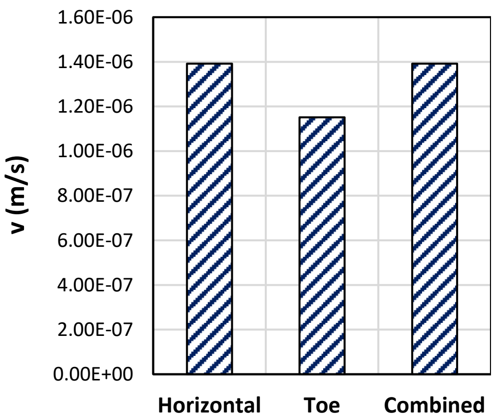


Figure 10-c. Relation between different types of drains and the water velocity (v)

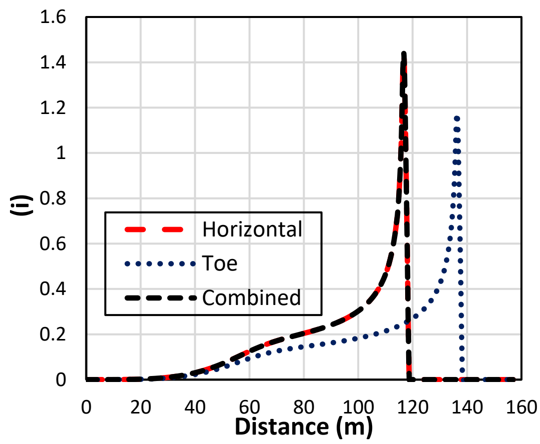


Figure 10-d. Relation between the base distance and the hydraulic slope (i) for downstream drains

5.4. Chimney drains

A comparison is performed between the vertical and inclined chimney drain with an angle of inclination equal to 45° with the same dimensions ($L/B = h_d/h = 0.25$) to know the influence of the chimney drain's inclination angle on the seepage properties. Figure 11-a illustrates the relation between the two chimney drains and the discharge coefficient (q/kh), from which it is seen that the seeped water quantity is a little higher in case of the inclined chimney drain compared to the vertical drain. This may be due to the decrease in the distance between the upstream side slope and the upstream face of the drain. The relation between the base distance and the pore pressure (PWP) for the two chimney drains is shown in Figure 11-b. It is indicated that there is no noticeable difference in the pore water pressure between the two chimney drains.

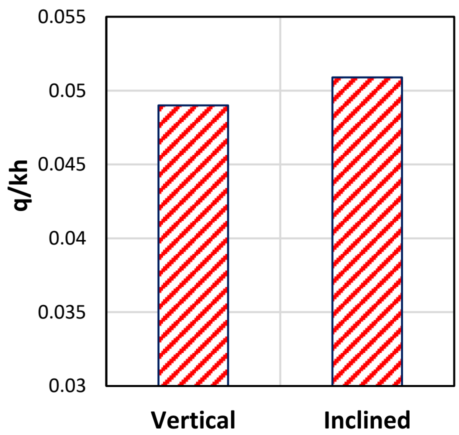


Figure 11-a. Relation between different chimney drains and the discharge coefficient (q/kh)

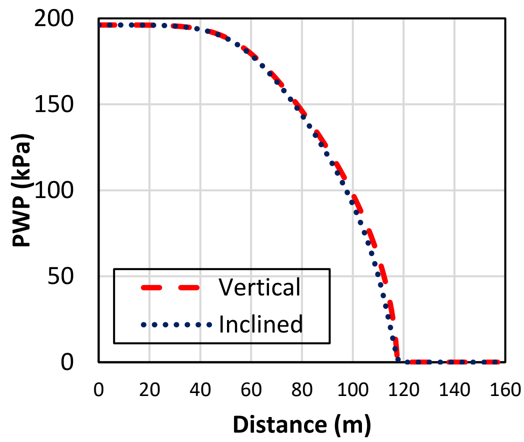


Figure 11-b. Relation between the base distance and pore pressure for the two chimney drains

Figure 11-c shows the relation between the two chimney drains and the water velocity (v). The chart shows that the velocity in the inclined chimney drain is lower than that in the vertical one (with about 95%). The relation between the base distance and the hydraulic slope (i) for the two chimney drains is shown in Figure 11-d. It is obvious that the gradient is significantly higher in the vertical chimney drain compared to the inclined drain (by about 95%), as the vertical chimney drain drives the flow to make a more sudden drop that increases the gradient.

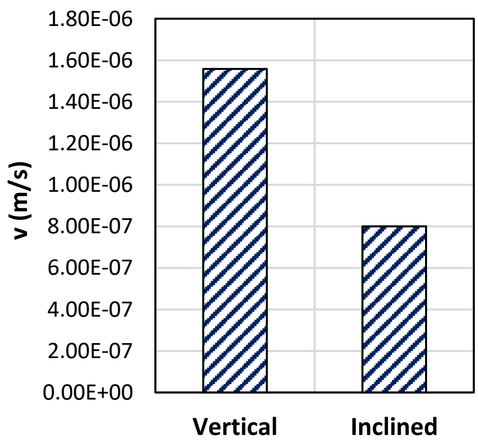


Figure 11-c. Relation between different chimney drains and the water velocity (v)

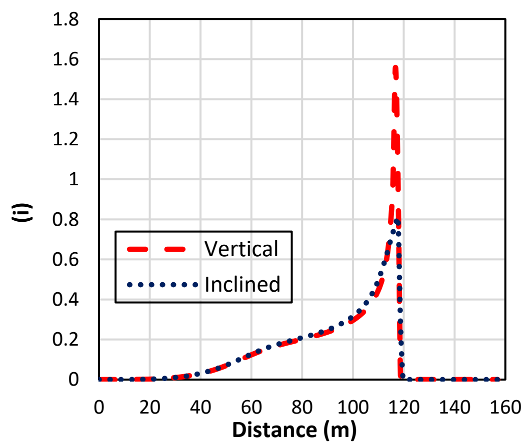


Figure 11-d. Relation between the base distance and the hydraulic slope (i) for the two chimney drains

6. Comparison between the different drainage systems

Some comparisons are introduced between the different effects of the downstream drains on the seepage characteristics. All the drains have the same horizontal length (L/B = 0.25) except the toe drain which has a relative length equal to 0.125 for a comparison between the horizontal, toe, and combined drains.

6.1. Effect on the seepage discharge

Figure 12 shows the influence of the different downstream drains on the discharge coefficient (q/kh). The chart illustrates that the maximum seepage discharge is obtained with the inclined chimney drain, while the inclined toe drain causes the minimum seepage discharge compared to the other drainage systems.

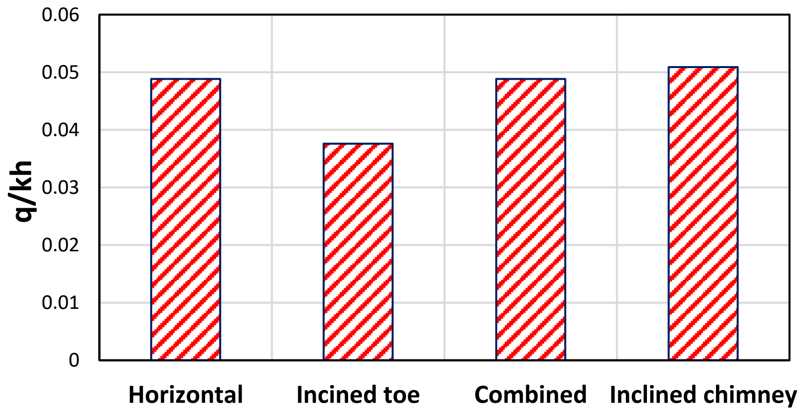


Figure 12. Effect of different types of drains on the discharge coefficient (q/kh)

6.2. Effect on the pore water pressure

The effect of the different drainage systems on the pore pressure (PWP) through the earth dam is illustrated in Figure 13. It is noticed that the case of the inclined toe drain has the maximum pore water pressure compared to other drains, and the minimum pore water pressure is in the case of the inclined chimney drain.

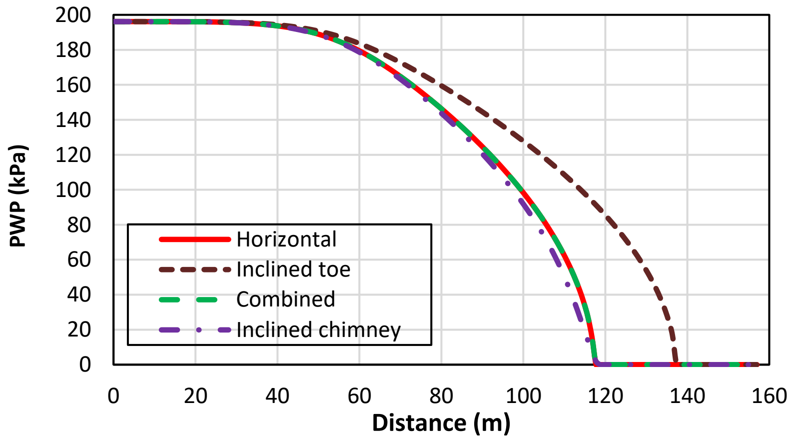


Figure 13. Relation between the base distance and the pore pressure (PWP) for the downstream drains

6.3. Effect on the water velocity

Figure 14 illustrates the effect of the different downstream drains on the water velocity (v). From the figure, the maximum water velocity through the earth dam is founded in the case of horizontal and combined drains, while the inclined chimney drain causes the minimum water velocity compared to the other drains.

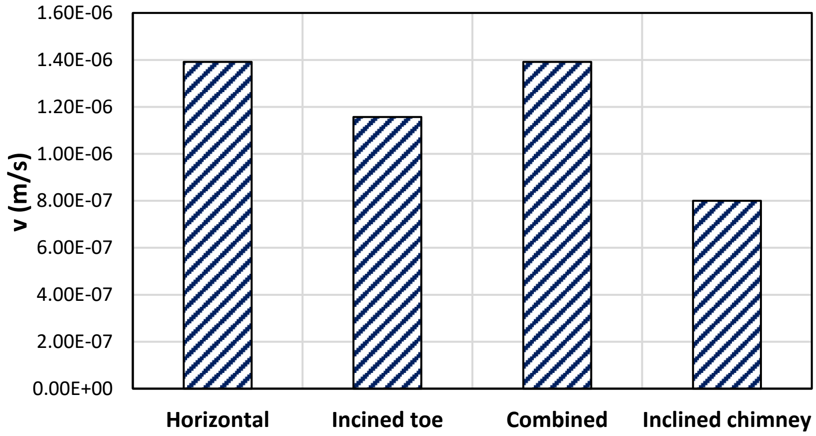


Figure 14. Effect of different types of drains on the water velocity (v)

6.4. Effect on the hydraulic slope

The effect of the different drains on the hydraulic slope (i) through the earth dam is shown in Figure 15. It can be concluded that the horizontal and combined drains have the maximum hydraulic gradients compared to other drains, and the minimum hydraulic gradient is obtained in the case of the inclined chimney drain.

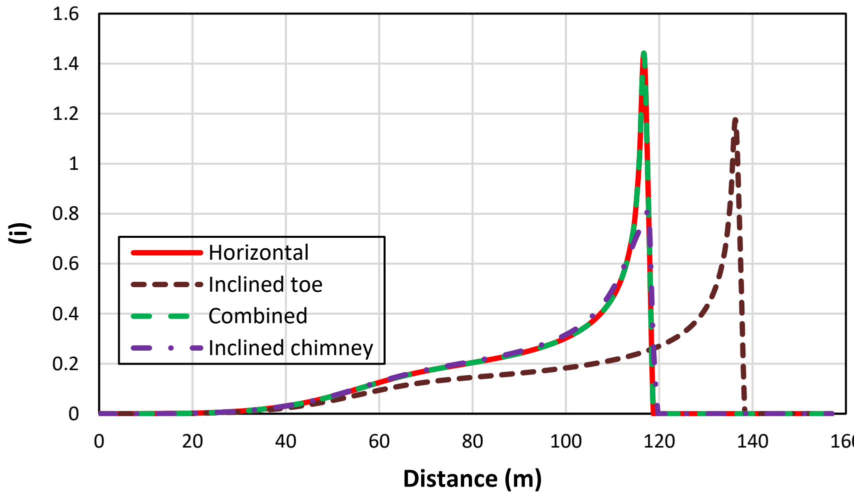


Figure 15. Relation between the base distance and the hydraulic slope (i) for the downstream drains

7. Conclusions

The study proves that using the SEEP/W model to simulate the seepage in embankment dams with downstream drains is a suitable tool, and the obtained results through it are in good agreement with the previous experimental and numerical studies. In the case of horizontal drains, the length of the drain is the most effective parameter in the performance efficiency, while the thickness has a negligible effect. For horizontal drains, 34% is the optimum length ratio (L/B) that gives minimum seepage through the earth dam. Increasing the length of the horizontal drain significantly increases the seepage discharge, while a noticeable decrease in the pore pressure in the dam body is obtained. In the case of using toe drains, the inside inclination angle of the drain has a slight effect on the seepage characteristics. The inclined chimney drain proves better performance than the vertical one in enhancing the dam properties against seepage.

Notations

B Bottom width of the dam (m).
b Top width of the dam (m).
H Total height of the dam (m).
h Upstream water head acting on the dam (m).
h_d Height of the chimney drain (m).
h_m Maximum head on the upstream side of the dam (m).
h_p Pressure head (m).
i Hydraulic slope (dimensionless).
k Hydraulic conductivity of the dam (m/s).
k_d Hydraulic conductivity of the drain (m/s).
L Length of the drain (m).
PWP Pore water pressure (kPa).
q Seepage discharge rate per unit length (m^2/s).
t Thickness of the drain (m).
v Water velocity in the x-direction (m/s).
X Distance from the beginning of the dam (heel) (m).
β Inclination angle of the drain (dimensionless).

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