FLOW BEHAVIOR AROUND PERFORATED TILE DRAINAGE PIPES

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ABSTRACT

The assumption of ideal drain performance is taken into consideration in the design and modeling of subsurface drainage system. In reality however, this is generally not so, and the flow encounters additional resistances due to pipe slotting and clogging around the drains. The present study is intended to investigate the effect of different parameters on the characteristics of subsurface drainage of irrigated land utilizing perforated tile drainage pipes. The saturated flow towards perforated drainage pipes is investigated by means of both laboratory experiments and numerical analysis. The effect of the perforation ratio of the pipe on the entrance resistance and exit hydraulic gradient was studied. The study was performed experimentally by using the sand box model technique and numerically by using energy balance method. Three soil types having different permeabilities were used. The perforation ratio of the drainage pipe was changed to take 3.3%, 4.96% and 6.62%. Two cases of water level were chosen. The results indicated that, the perforation ratio affects not only the seepage discharge but also the water table elevation for the flow towards the pipe. Increasing the perforation ratio of drainage pipe causes an increasing of the seepage flow towards the drain. It was found also, that the coefficient of entrance resistance decreases with the increase of both the perforation ratio and the mean diameter of soils. For fine texture soils and for high perforation ratio, the coefficient of entrance resistance is increased. So, it is concluded that the use of envelope from coarse soil around the pipe will decrease the soil clogging and hence the entrance resistance. The numerical results show reasonable agreement with the experimental ones.

Key Words: Entrance Resistance, Subsurface Drainage, Perforated Pipes, Exit Gradient.

INTRODUCTION

The increased and the perennial supply of water to the irrigated land causes the water table to rise and introduces more salts than before, even though the quality of water is good and its salt content is low. The rise of the water table was aggravated by new irrigation projects in the higher desert lands bordering valley and delta. The shallow water table impeded leaching of salts with an extra dose of irrigation water. Together with the heavy clay nature of the soils, through which the downward percolation of water is limited, some soil salinity problems start to develop and crop yields could be affected.

Agricultural land drainage at a large scale has been practiced in Egypt since the middle of 20th century. The problem of subsurface drainage has been investigated using different lines of approach, Oosterbaan [11, 12]. Many investigators have provided rational formulas for the design of drainage systems with special refers to the calculation of drain spacing, Wiskow and van der Ploeg [18], Das [3], and Kohler et al. [10]. Most of the theoretical investigations on tile drainage operation assumed the drain to be ideal, i.e. neglect the effect of pipes perforations and pipes diameters on the real flow pattern in the vicinity of pipes. However, recently some researchers among of them Gratin [8] and Bentley and Skaggs [1] showed the effect of envelopes on the flow pattern near the drain pipes and the changes in entrance resistance of subsurface drains. Skaggs [17] and Dierickx [4] studied the head losses which were resulted from the stream lines converging toward a finite number of tube openings. The installation of drain tubes requires the soil around the drain to be disturbed. The soil disturbance during drain installation will decrease the resistance to flow and it may take years to return to its original condition [16]. Also, the migration of fine particles may result in change in soil conditions in the immediate vicinity of the drain. The fine particles may migrate out of the soil and into the drain tube resulting in a decrease in the resistance to flow. Conversely, the migrating particles may become lodged in small pores in the soil, at the soil-drain interface, or in the envelope, and increase the resistance to the flow [2].

The purpose of this study is to clarify the precise behavior of flow towards perforated drainage pipes in different types of soil and the way by which the perforated pipes behave in these soils. Different perforation ratios and water levels were chosen in an attempt to improve drainage design criteria, hoping that the results will help for field applications.

THEORY

Agricultural drainage systems entail the flow of pore water through both unsaturated and saturated soil. Ignoring the compressibility of water and soil, the flow of water through a variably saturated soil into drains is described by two-dimensional Richards equation for anisotropic conditions, Rodgers et al. [14].

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[k_x \frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_y \frac{\partial h}{\partial y}\right] \pm R \tag{1}$$

where θ is the volumetric water content (m^3/m^3), t is the time (s), k_x and k_y are the hydraulic conductivity in both the horizontal and vertical directions, respectively (m/s), h is the total hydraulic head (m), and R is the rate of change in the volume of water per unit time for unit volume of soil, e.g. rainfall or irrigation or evaporation.

For steady state conditions, the total potential head, h, within a flow domain with known boundary conditions is governed by Laplace's equation:

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} \pm R = 0 \tag{2}$$

A wide variety of methods exist for solution. The methods include analytical solution, Hathoot [9], sand tank model, Gratin [8], and numerical methods, El-Attar and Mosia [5] and Saafan [15].

Oosterbaan et al. [13] introduced the concept of energy balance of groundwater flow. It is based on equating the change of hydraulic energy flux over a horizontal distance to the conversion rate of hydraulic energy into friction of flow over that distance. The energy flux is calculated on the basis of a multiplication of the hydraulic potential head and the flow velocity, integrated over the total flow depth. The conversion rate is determined in analogy to the heat loss equation of an electric current. This concept is applied to subsurface drainage by pipes and has the possibility to introduce entrance resistance and/or layered soils with anisotropic hydraulic conductivities.

Assuming; 1) steady state fluxes, i.e. no water and associated energy is stored, 2) vertically two-dimensional flow, i.e. the flow pattern repeats itself in parallel vertical planes, 3) the horizontal component of the flow is constant in a vertical cross-section, and 4) the hydraulic conductivity of the soil is constant, it is found that:

$$\frac{dh}{dx} = -\frac{v_x}{k_x} - \frac{q_R(h-H)}{v_x h} \tag{3}$$

where h= the total hydraulic head at horizontal distance, x from drain center-line, taken with respect to the level of the impermeable base of the aquifer (m), H = a reference value of h (m), v_x = the apparent flow velocity at distance x in horizontal x-direction (m/day), dx = a small increment of distance x (m), dh = the increment of h over the increment dx (m), $\frac{dh}{dx}$ = the gradient of the water table at x (m/m) and q_R = the recharge (m/day).

The last term of Eqn. (3) represents the energy associated with the recharge q_R. When recharge q_R is zero, Eqn. (3) yields Darcy's equation. The negative sign of v_x indicates that the flow is positive when the gradient $\frac{dh}{dx}$ is negative, i.e. the flow follows the descending gradient, and vice versa. Equation (3) is solved numerically where the flow is divided to a radial flow in the near of the pipe and a horizontal flow in the far of the pipe.

EXPERIMENTAL WORKS

Experiments were conducted in sand tank (1.50 m long, 1.00 m wide and 0.75 m high (see Fig. 1)). A P.V.C. pipe was installed horizontally in the mid of the tank and its centerline was 20 cm above the tank bottom. The tank was filled with soils compacted in layers each 200 mm thickness. Water was supplied to the soil from both sides at a constant hydraulic head. A grid of tiny piezometers for measuring hydraulic head distribution was fixed in the tank and was connected by plastic tubing to manometers.

The diameter of drainage pipe was taken 30 mm. The perforation ratio was changed three times to take 3.3%, 4.96% and 6.62%; arranged at 4, 6, and 8 rows respectively. According to FAO [7], the perforations were spaced 20 mm apart and have a diameter 4.5 mm. The hydraulic heads on both sides were changed two times; one is same at the two sides, while the other has the left hand side head higher than the right hand side by 150 mm. Three types of soils were used. Figure 2 shows the gradation curve for each soil type and Table (1) shows the soil properties. For each case, the discharge rate and the piezometric levels were recorded after steady state flow was reached. For a given experiment the upstream head, soil type and perforation ratio were fixed and the corresponding piezometer levels and outflow rate were measured.

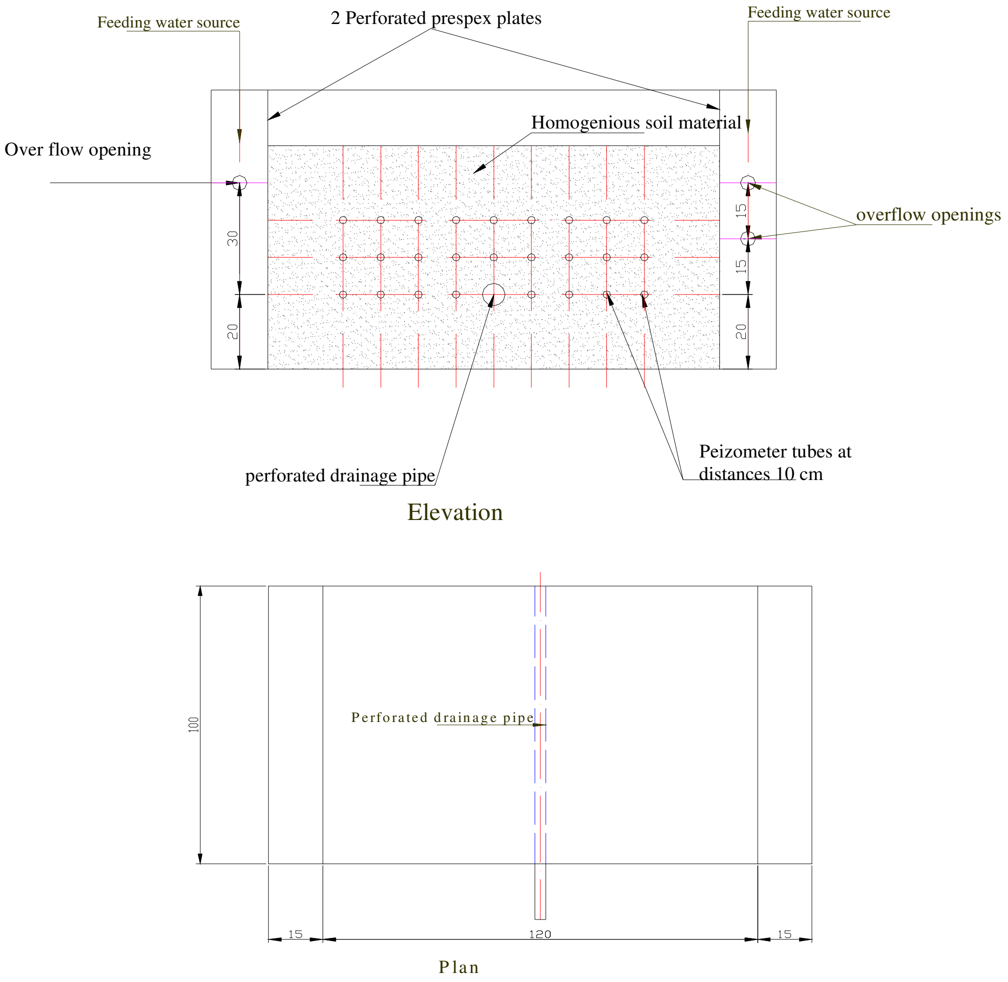


Fig. 1: Large sand tank: Laboratory set-up (all dimensions in cm)

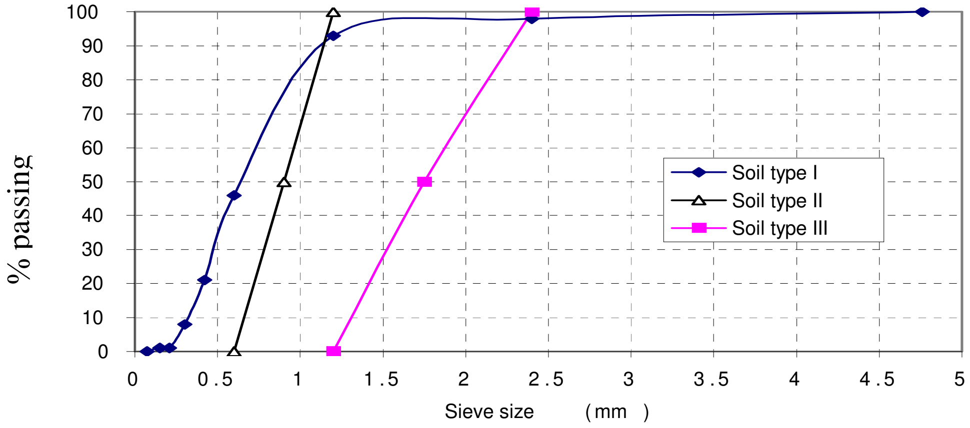


Fig. 2: Gradation curves for the soils used in the experiments

Table (1): Properties of soils used in the experiments

Soil type	I	II	III
d_{50} (mm)	0.6	0.9	1.75
K (m/day)	6.739	44.928	182.304

ANALYSIS AND DISCUSSIONS OF RESULTS

The flow pattern near the drain is very complex due to the disturbed soil where physical characteristics are heterogeneous and are changed with the time and are, therefore, difficult to predict. The drained flow and water table profile depend on many parameters; some of them are relating to the geometry of flow and the others are relating to the soil properties. Figure 3 shows a definition sketch of variables used in the analysis.

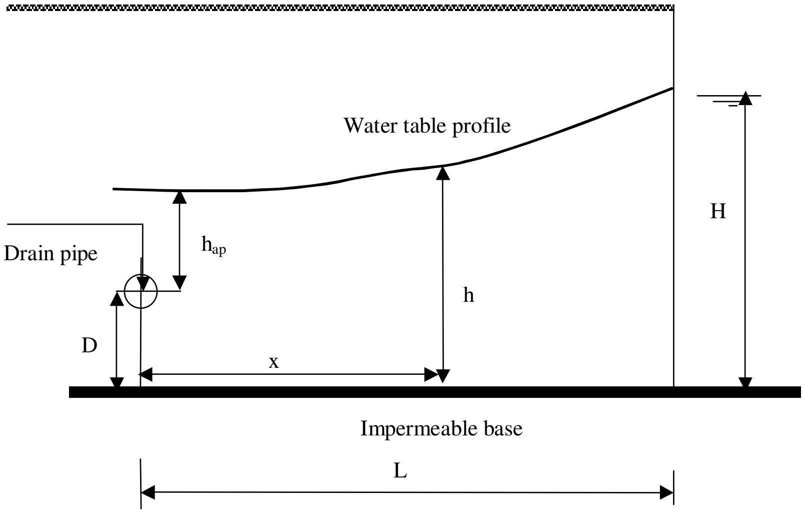


Fig. 3: Definition sketch of variables

ENTRANCE RESISTANCE

According to Ernst [6], the flow towards a subsurface drain can be described by a vertical flow (from the water table downward to drain level), a horizontal flow towards the vicinity of the drain, a radial flow to the drain and an entry into it. Each of these flows is subjected to a corresponding resistance (Fig. 4). For steady state flow, the total resistance can thus be roughly classified into vertical, horizontal, radial, and entrance resistances. Differences in heads are measure of these resistances. The total loss of head, h_t, is the sum of all differences indicated in Fig. 4b.

The relationship between the head loss and the corresponding resistance is given by:

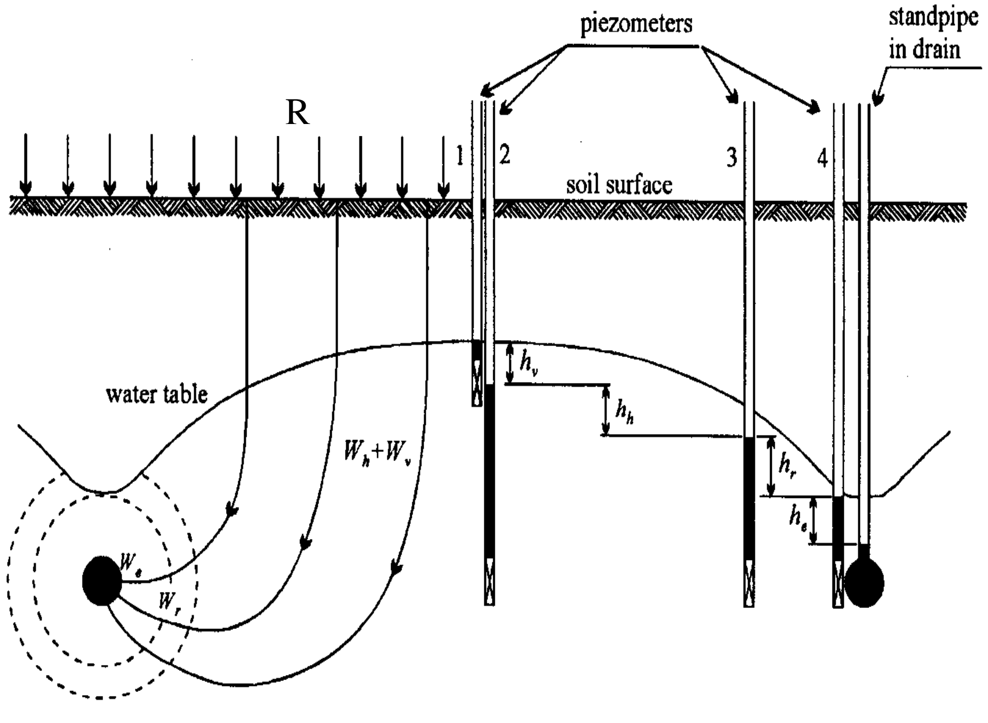
$$h_t = qW \tag{4}$$

where h_t is the total difference in head (m), q is the drainage discharge per unit length (m^2/day), and W is the resistance (day/m).

Sometimes the resistance W is replaced by the dimensionless quantity α, which is dependent on the hydraulic conductivity of the soil:

$$\alpha = kW \qquad \text{or} \qquad W = \alpha / k \tag{5}$$

where k is the hydraulic conductivity (m/day) and α is a geometrical factor (dimensionless).



(a) (b)

Fig. 4: Flow resistance towards a drain (a) and their corresponding head losses (b)

As compared to the flow to an imaginary, ideal drain, the convergence of streamlines to the inlet perforations of a real drain invokes an additional flow resistance and head loss. The additional flow resistance is called entrance resistance and the corresponding head loss is the entrance head loss. According to Eqn. (4) and taking into account Eqn. (5), the relationship between entrance head loss and entrance resistance is given by:

$$h_e = qW_e = \frac{q}{k}\alpha_e \tag{6}$$

The entrance resistance of a real drain can be calculated theoretically for some simple perforation shapes and patterns, or can be obtained if the flow pattern towards both ideal and real drain can be accurately modeled. In most cases, the entrance resistance is obtained empirically from the entrance head loss. Theoretically, the entrance head loss can be obtained directly from piezometer readings outside and inside the drain (Fig. 4b). Practically, however, piezometer 4 (see Fig. 4b), will be placed at short distance away from the drain to avoid the disturbance of the soil and therefore, the measured head loss involves not only the entrance head loss, but also part of the radial resistance. Fig. 5 shows the calculated values of entrance resistance coefficient, W_e from Eqn. (6), versus perforation ratio $p_r\%$ for the studied soil types. It can be noticed from this figure that the entrance resistance coefficient decreases by increasing the perforation ratio for both soil II and III. At case of soil type I, the entrance resistance coefficient for perforation ratio 6.6 % is higher than that for perforation ratio 4.9 %, this is due to the fact that the grain size gradation of soil type I has a wide range which causes clogging of the fine material around the pipe and subsequently increases the resistance around the pipe. In comparison between Fig. 5 and Fig. 6, it is shown that, W_e decreases with the increase of H/D ratio and the effect of clogging of fine materials around the pipe on W_e decreases by the decreasing of H/D ratio.

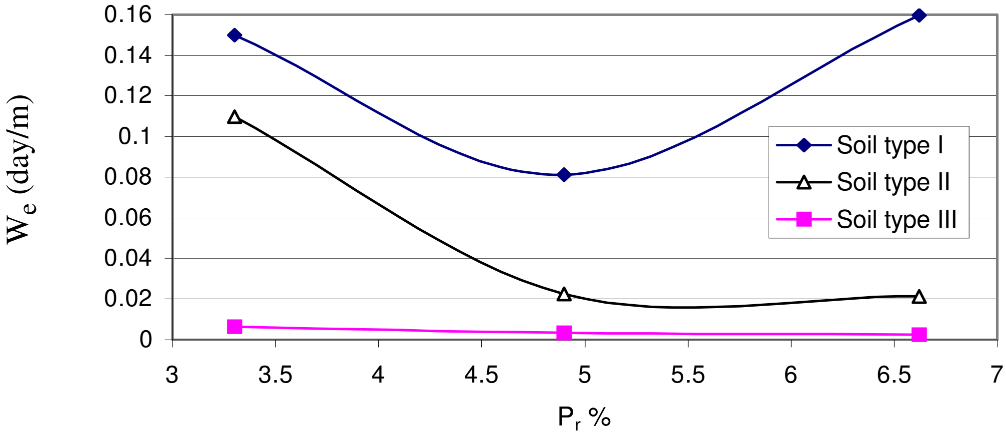


Fig. 5: Values of entrance resistance versus perforation ratio at $H/D = 2.5$

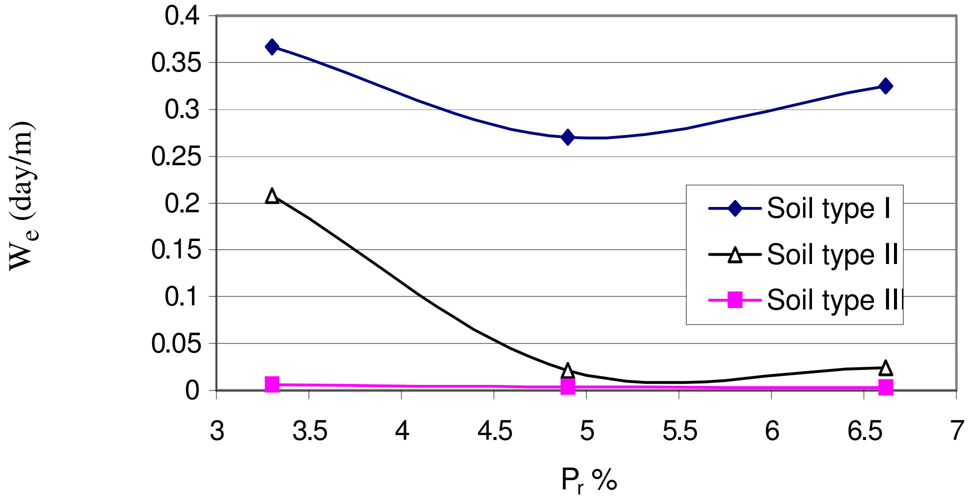


Fig. 6: Values of entrance resistance versus perforation ratio at H/D = 1.75

EXIT GRADIENT

Darcy's law describes the proportionality between the discharge, Q over a cross sectional area, A and the hydraulic gradient, i as follows;

$$Q = k\,A\,i \tag{7}$$

By the same way the hydraulic gradient at the pipe can be expressed as;

$$i_{ex} = \frac{q}{2\pi k R_o} \tag{8}$$

in which R_o is the radius of the pipe.

Considering radial flow towards an ideal drain, i.e. a completely permeable drain, the exit hydraulic gradient i_{ex} where the water leaves the soil and enters the drain will be greater than anywhere else in the flow system. It is inversely proportional to the drain radius. For non-ideal drainpipes, the flow lines further converge toward the perforations in the drain wall, so that the exit gradient at the drain perforations will be even greater. Figure 7 shows the variation of the exit hydraulic gradient with the perforation ratio for different soil types, where i_{ex} is computed using Eqn. (8). It is noticeable that i_{ex} increases by increasing the perforation ratio and this have a bad effect on the stability of the soil around the pipe. For this, it must be checked that the exit hydraulic gradient should be less than the critical hydraulic gradient for the incipient motion of soil around the pipe, else an envelope must be used. Furthermore, the radial flow occurs over only a section of the drain circumference, therefore it is expected that the exit hydraulic gradient value is higher than that computed using Eqn. (8).

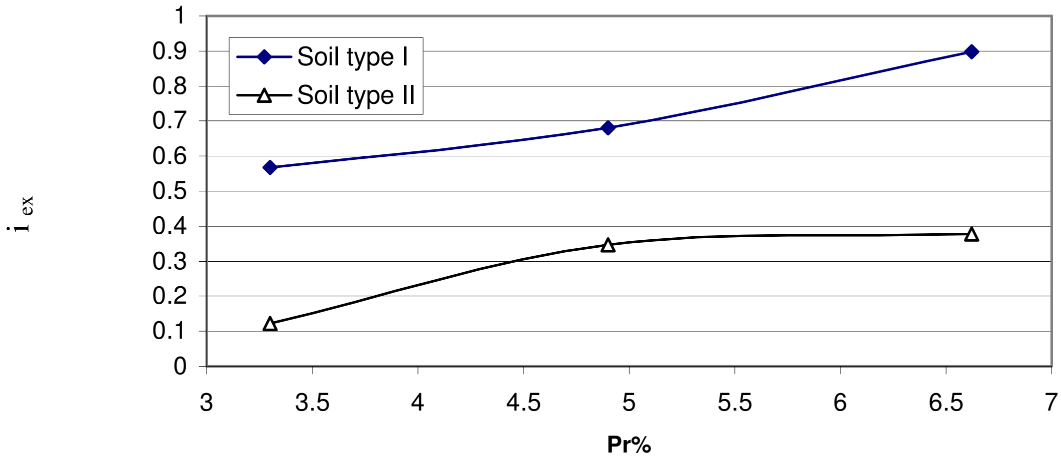


Fig. 7 : Exit gradient versus perforation ratio at H/D = 2.5

WATER TABLE PROFILES

Figures 8 and 9 show the experimental (solid lines) and the numerical results of Eqn. (3) (dashed lines) for h/D versus x/L at the studied H/D ratios and soil types I and III, respectively. It is shown from these figures that the piezometric head h/D increases by increasing the relative head H/D for the same soil type and perforation ratio. Also, it is noticeable that the water table takes the same trend for different values of H/D. There is a fairly good agreement between both the theoretical and experimental results. The deviation near the pipe is due to the interpolation of the measured data to the center-line of the pipe and the deviation at the far side of the pipe is because of head loss due to entering the water from feeding tank to the soil. Both the experimental and numerical results show that, the reference head H has a noticeable influence on the water table profile.

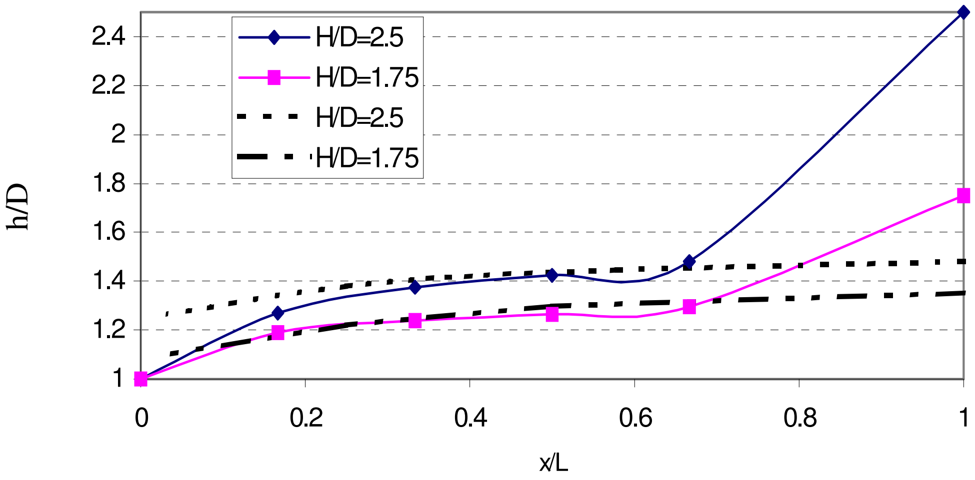


Fig. 8: Comparison between the measured (solid lines) and the computed (dashed lines) h/D versus x/L for H/D = 2.5 and 1.75 at soil type I and perforation ratio = 3.3 %

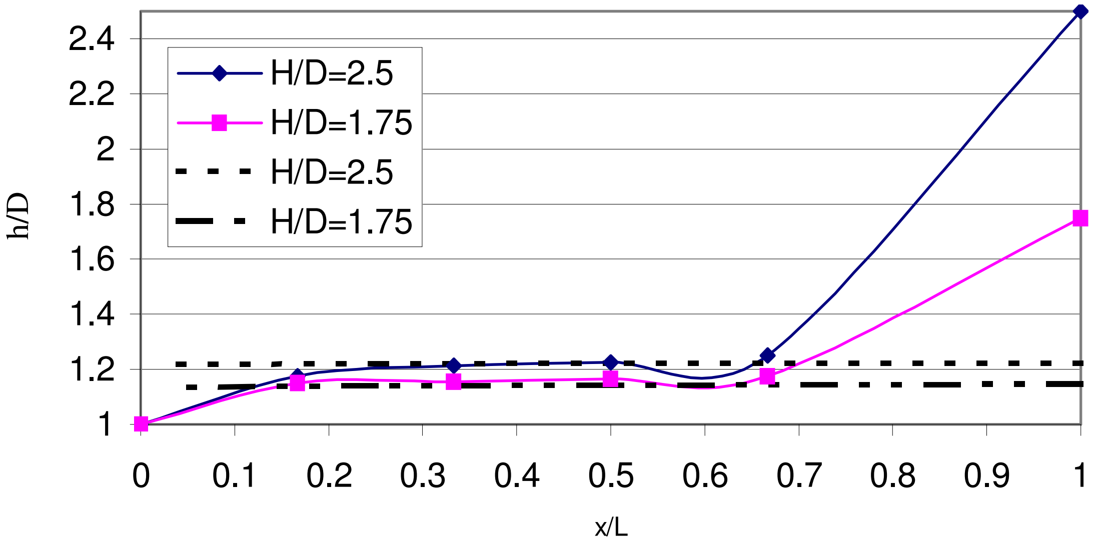


Fig. 9: Comparison between the measured (solid lines) and the computed (dashed lines) h/D versus x/L for H/D=2.5 and 1.75 at soil type III and perforation ratio = 3.3 %

For the same value of relative head H/D and perforation ratio $p_r\%$, Figure 10 shows the variation of the piezometric head h/D with the horizontal distance x/L for the different types of soils. It can be shown that the values of the piezomertic head decreases by increasing the mean diameter of soil grain size or hydraulic conductivity. Also, it is seen that the inclination of water table towards the drainage pipe takes three stages; the first one near the pipe where the water table is rapidly decreased, the second one is the gradually decrease of the water table far from the pipe, while the third one is the rapid decrease of the water table near the feeding tank.

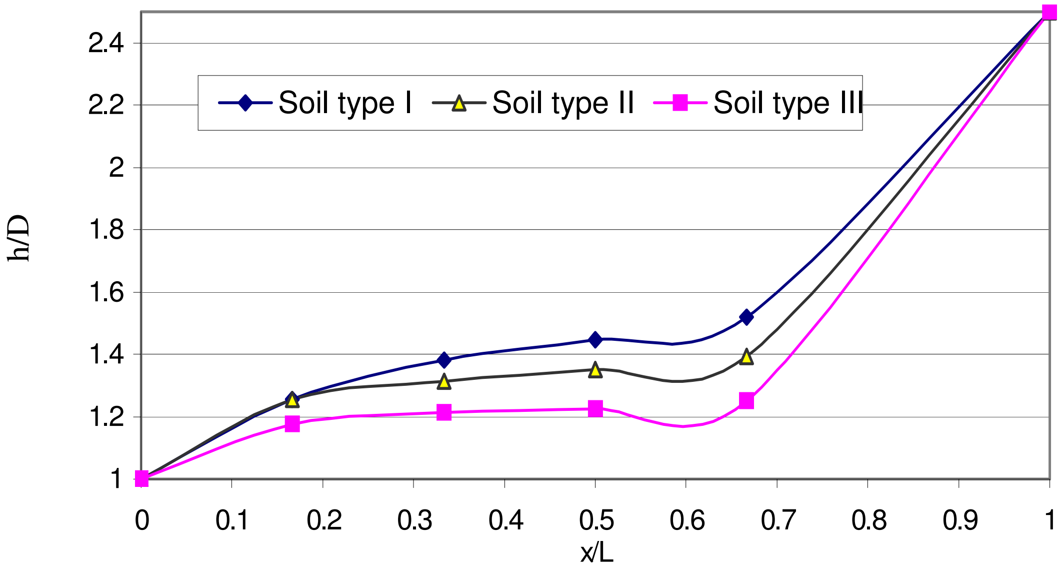


Fig. 10: Comparison between the measured h/D values versus x/L for different soil types at H/D=2.5 and perforation ratio = 3.3 %

DRAINAGE-PIPE DISCHARGE

The discharge capacity of drainpipes is an important component of any design procedure for land drainage systems. The effect of perforation ratio of pipe, $p_r\%$, on the seepage discharge, q (cm^2/min) per unit length of the pipe, is shown in Fig. 11. From this figure, it is clear that, when the type of soil is constant, the value of seepage discharge is directly proportional to the values of perforation ratios. Also, it can be noticed that, the effect will be higher in coarse soil and this effect may be reduced in fine soils.

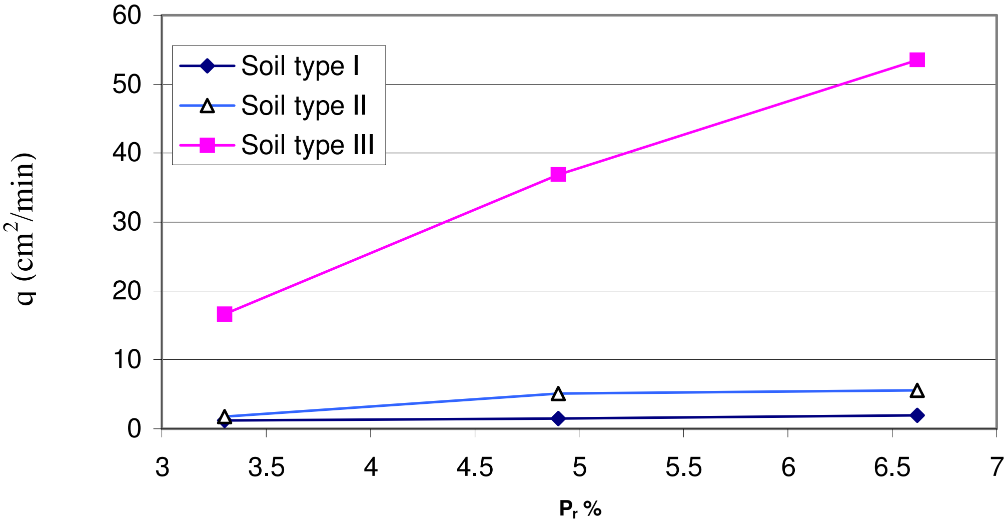


Fig. 11: Drainage-pipe discharge versus perforation ratio for different soil types at $H / D = 2.5$

CONCLUSIONS

On the basis of the present study, it can be concluded that, the sand tank method allows one to increase the knowledge of the water flow pattern near the drain pipe under field-like boundary conditions and allows comparison of different perforation ratios behavior. It also mitigates the effect of upstream water level and soil type on the flow pattern.

Design criteria usually do not consider the approach flow resistance and perforation ratio because it is supposed the ideal drainage pipe. However, the drain approach flow resistance results a noticeable approach flow head loss.

Application of the energy-balance to groundwater flow towards drainage pipe gives a representation of the shape of the water table. The computed results and the measured ones for water table have a reasonable agreement. Also, the experimental and the numerical results indicated that:

1) Entrance resistance has a considerable effect on the flow around perforated pipes and must be taken into consideration in the design.
2) Entrance resistance is affected by the clogging of the soil around the drain and therefore increases with the time.
3) The seepage discharge increases by increasing the values of the pipe perforation ratio and soil hydraulic conductivity.
4) The exit hydraulic gradient increases by increasing the perforation ratio.

NOMENCLATURE

D = height of the drain pipe from the impermeable layer
d = diameter of drain pipe
H = a reference value of head h
h = potential head at any distance x from the pipe centerline
h_{ap} = approach flow head above the pipe
i_{ex} = exit hydraulic gradient
k_x = hydraulic conductivity in x-direction.
k_y = hydraulic conductivity in y-direction
L = distance from the drain pipe to the reference head H
p_r = perforation ratio
q = drain pipe discharge per meter length
q_R = recharge
R = applied boundary flux
v_x = apparent flow velocity at x in x-direction
W = flow resistance to the drain
α_e = dimensionless entrance resistance coefficient

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