International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Research Article

Drainage Design Equation for Egyptian Vertisols

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Accepted 10 July 2015, Available online 23 July 2015, **Vol.5, No.4 (Aug 2015)**

Abstract

Egyptian Vertisols have high productivity and have a moderate to high fertility. It has a very high water-holding capacity, but most of the water is tightly bound and not available to plants. Vertisols are heavy clay soils that show significant expansion and contraction due to the presence or absence of moisture. Deep and wide cracks in a polygonal pattern are formed as a result of this process. Most Egyptian Vertisols areas have poor productivity due to salt affected soils and waterlogging. Water management in such lands needs much attention. An understanding of the hydraulic properties of heavy clay soils is obviously of importance in assessing their potential for reclamation. The objective of this paper is to take into consideration the effect of top cracking layer on the conveyance of water to the drains in heavy clay soil. The unsteady state equation for design spacing between subsurface field drains is developed for use in cracking Vertisols. Compared with the Glover-Dumm equation, the new equation calculates wider spacing ranged between 38% and 54% for different hydraulic conductivity values varied between 0.10 and 0.50 m/day.

Keywords: *Drainage, Design, Vertisols, Cracks.*

1. Introduction

Vertisols are clay-rich soils that shrink and swell with changes in moisture content. During dry periods, the soil volume shrinks, and deep wide cracks form. The soil volume then expands as it wets up. This shrink/swell action creates serious engineering problems. Vertisols and associated soils cover approximately 257 million ha (1 ha = 10,000 m^2) of the earth's surface in 76 countries (Dudal and Bramao, 1965). In Africa it covers vertic soil cover 43 million ha in 28 countries in Africa (Latham, 1987). (Virmani, *et al*, 1982) mentioned that the major areas of Vertisols are found in Australia (70.5 million ha), India (70 million ha), Sudan (40 million ha), Chad (16.5 million ha) and Ethiopia (10 million ha). Due to their high clay content, the physical properties of Vertisols are greatly influenced by moisture content; usually, these soils are too sticky and unworkable when wet, and very hard when dry. (Rycroft and Amer, 1995) mentioned that Vertisols are potentially a highly productive group of African soils. If properly managed, they could be highly productive, but are highly prone to erosion. Water management in such lands needs much attention, especially for limited productive land and water resources with incredible growing population. One effective way to reduce waterlogging and salinity problems is the land drainage. (Hussein, *et al*, 2000) defined Vertisols as clay soils with clay content of 40% or more, hydraulic conductivity of 0.1 m/day or less, high shrinkage and swelling potential and high salinity as well. In Egypt, vertisols represent approximately 260,000 feddans (1 feddan= 4200 m^2) located in the northern parts of the country, south of lakes Edco, El Buruls and El Manzala, south Port Said and Tina Plain of north Sinai as shown in Figure (1). The soils in these areas consist of marine clays, which are highly saline and have poor internal drainage properties. The sodicity hazard in these soils is high and their permeability is very low and reclamation is very difficult and expensive. Water management in such lands needs much attention, especially for limited land and water resources with incredible growing population.

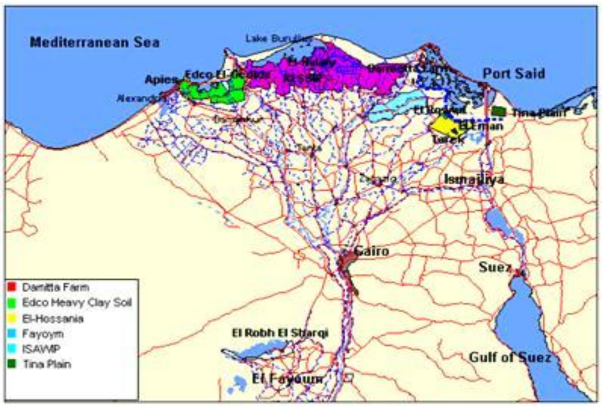

Fig. 1 Location of Vertisols areas in Egypt

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An understanding of the hydraulic properties of heavy clay soils is obviously of importance in assessing their potential for reclamation since the lack of flow of water through them is a constraint preventing reclamation (Abrol, *et al*, 1988). (Nijland, *et al*, 2005) clarified that the one effective way to reduce waterlogging and salinity problems is drainage and the objective of any form of land drainage is to control the position of the water table. (Tuohy, *et al*, 2015) mentioned that the mole drain is the most effective drainage method in Irish Vertisols.

Disposal of drainage effluent is a major issue associated with subsurface drainage system. Without proper disposal of drainage effluent, environmental problems may arise. Subsurface drainage improves the productivity of poorly drained soils by lowering the water table, creating a deeper aerobic zone and enabling faster soil drying and improving root zone soil layer condition (Jung, *et al*, 2010). Subsurface drainage induces a decrease in the intensity of erosion and an increase in the intensity of lixiviation and eluviation, as well as specific redox processes, compared to similar undrained soils (Montagne, *et al*, 2009). The narrow drain spacing is required to drain the heavy clay soils of low hydraulic conductivity. The hydraulic conductivity may be so low that no subsurface drainage with economically justifiable spacing is possible (Ritzema, 2014).

The cracks network has high influence on the water flow to the low permeable sub-layers. The soil moisture distribution after field irrigation is influenced to a large extent by the occurrence of cracks in the soil profile (Nova´k, *et al*, 2000). (Grismer, 1992) mentioned that cracking clay soils pose a unique set of problems related to water management. It may have an apparent drainable pore space or specific yield as large as 10%. Such a value of specific yield is useful in designing irrigation and drainage systems for cracking clay soils. (Valipour, 2014) mentioned that heavy clay soils show a very distinct feature under dry and wet conditions. The appearance of shrinkage cracks due to the decrease of soil volume when they are drying. Upon wetting, the cracks close again and the soil surface rises. These soils have a very good ability to improve their structure through drying/wetting. (Arnold, *et al*, 2005) reported that the seasonal cracking of the soil matrix results in poor estimates of runoff and infiltration by simulation models due to the changing soil storage conditions. They examined and discussed the relationships between measured crack volume and hydrologic variables simulated by model. (Dinka, *et al*, 2013) mentioned that an understanding of the hydraulic properties of heavy clay soils is obviously of importance in assessing their potential for reclamation since the lack of flow of water through them is a constraint preventing reclamation. The soil moisture distribution after field irrigation is influenced to a large extent by the occurrence of cracks in the soil profile. (Uday and Singh, 2013) reported that many studies dealing with cracking characteristics of the fine-grained soils focus on establishing the influence of various factors affecting cracking, after effects of cracking, and cracking patterns. Mathematical models have also been developed based on the experimental results, from these studies, to estimate time of initiation of the crack, water content at this instant, and the depth up to which these cracks propagate. (Ebrahimian and Noory, 2014) proved the importance of cracks in subsurface drainage system of paddy fields. (Kumar, *et al*, 2012) found that modified Glover equation was appropriate to assess the hydraulic heads and the drain discharge. Therefore, this equation is suggested for use to predict drain spacing and drain discharge on daily basis for the design of drainage structures including evaporation ponds for the disposal of drainage effluents. (Yousfi, *et al*, 2014) referred that that most drain spacing calculations do not take the horizontal flow in the unsaturated zone above the groundwater table into consideration.

They suggested that inclusion of the contribution of the unsaturated zone flow in the computation of drain spacing may result in greater economy in the design of subsurface drainage systems. (Pali, 2013) predicted the hydraulic heads quite close to the measured hydraulic heads using Van Schilfgaarde, Modified Glover, and Integrated Hooghoudt equations for drainage design. Among these three equations, Modified Glover equation was the most superior. (Ritzema, 1994) remarked that the Glover-Dumm and the De Zeeuw-Hellinga equations can only be applied in soil with a homogeneous profile. Also, the flow in the region above the drains is not taken into account. When the depth of the water table above drain level (h) is large compared to the depth of the impervious layer (d_e), an error may be introduced. However, the biggest restriction is the introduction of drainable pore space into the equations.

2. Materials and methods

The main reason for introducing the new design equation in cracking heavy clay soil is to take into consideration the effect of top cracking layer on the conveyance of water to the drains.

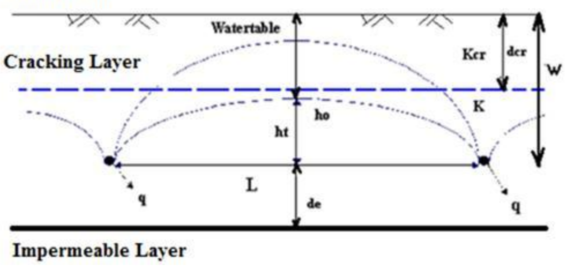

Fig. 2 Drainage in cracking heavy clay soil

The proposed un-steady state equation for drain spacing depends on the drainage base depth (W), which includes crack depth (d_{cr}) in the cracking layer of the hydraulic conductivity (K_{cr}) and the sub-layer of depth (H) with the hydraulic conductivity (K) as shown in Figure (2). Also, it depends on the equivalent depth (d_e) of Hooghoudt's equation to the impermeable layer, drainable pore space of the soil profile (μ) and drainage resistance (D_R) which is function of time to drop the water table from ground surface (h_o=W) to ht.

2.1 Theory

2.1.1 Boundary conditions

It is assumed that two-dimension flow domain is bounded from the top by a free surface at atmospheric pressure. The bottom boundary is an impervious layer at a depth of 5.0 m from land level. There is no recharge. The initial watertable at ground surface is lowered with the time. The top layer represents cracking zone followed by sub-layer of very low permeability.

2.1.2 Water balance

The water balance of the soil profile can be written as:

$$I - E_T - E_{cr} - q = \frac{\Delta S}{\Delta t} \quad (1)$$

$$R - q = \mu \frac{\Delta h}{\Delta t} \quad (2)$$

Where:
I: Quantity of applied Irrigation per unit surface area over the time (mm/d); E_T: The rate of Evapotranspiration from the root zone (mm/d); E_{cr}: The rate of Evaporation from the surface area of cracks (mm/d); q: Drainage discharge per unit surface area (mm/d); ΔS: Change of water storage per unit surface area (mm); Δt: The computation interval of time (day); R: The net Recharge to the soil profile (mm/d); μ: The mean value of drainable pore space in soil profile ($m^3.m^{-3}$); Δh: The change of watertable head (m).

If there is no recharge to the groundwater, then the change in the soil profile storage (ΔS) will be equal to the drain rate (q) i.e.:

$$q = -\mu(\frac{\Delta h}{\Delta t}) \quad (3)$$

The solution is based on the consideration that the fall of watertable is accompanied by removal of a certain amount of water storage. This amount is assumed equal to the quantity of irrigation water needed to produce a rise of the same magnitude. The flow percolates vertically and horizontally in cracking layer downward towards the watertable. In the saturated zone below watertable, the flow continues more or less in a vertical direction but soon turns horizontally towards the drains. A horizontal flow under the drainpipe is assumed. The radial flow is not taken into account due to the shallow impervious layer from the pipe drain and consider the imaginary equivalent depth of Hooghoudt (d_e) i.e. $d_e << L$ in similarity to steady-state approach. Then it does not take into account the extra head loss caused by the converging flow towards the drainpipe. It can be assumed that the total head loss (h) is due to vertical and horizontal flow.

$$h = h_v + h_h \quad (4)$$

2.1.3 Vertical head loss h_v

The head loss due to vertical flow in a cracking layer of thickness (d_{cr}) and hydraulic conductivity (K_{cr}) and through a sub-layer of thickness (H) and hydraulic conductivity (K) is given by:

$$h_v = q(\frac{d_{cr}}{K_{cr}} + \frac{H}{K}) \quad (5)$$

The head losses due to vertical and horizontal flow are illustrated in Figure (3).

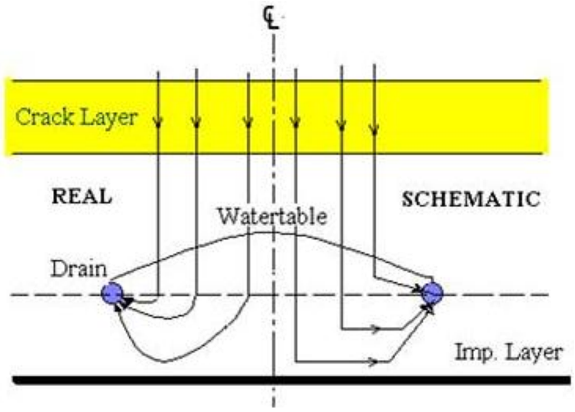

Fig. 3 Drainage flow pattern

2.1.4 Horizontal head loss h_h

According to the Depuit-Forrchheimer theory, Darcy's equation can be applied to describe the flow of groundwater (q_x) through a vertical plan of unit width as shown in Figure (3).

$$q_x = KD\frac{dh}{dx} \quad (6)$$

Where q_x = unit flow rate in the x-direction (m^3/d); K = hydraulic conductivity of the soil (m/d); D = conceptual average thickness of the horizontal flow zone (m); dh/dx = the hydraulic gradient at distance x (-).

The continuity principle requires that all the water entering the soil must be released to drains of spacing (L). Then if the recharge rate (q) enters the soil, the flow per unit area (q_x) through vertical plan is:

$$q_x = q(L/2 - x) \quad (7)$$

Equating equation 6 and 7 and integrating for x=0, h_x=0 and x = L/2, h_x = h_h.

$$q\int_0^{\frac{L}{2}} (L/2 - x)dx = KD\int_0^{h_h} dh_x \quad (8)$$

Resulting:

$$h_h = \frac{qL^2}{8KD} \quad (9)$$

The horizontal flow zone takes place in cracking layer of transmisivity $K_{cr}d_{cr}$ and sub-layer of transmisivity Kd_e and it can be written as:

$$h_h = \frac{qL^2}{8K_{cr}d_{cr} + 8Kd_e} \quad (10)$$

If the impervious layer is very shallow, the value of Kd_e decreases and consequently the horizontal head loss increases sharply. The equivalent depth de of Hooghoudt's assumption replaces the imaginary shallower impervious layer above the real one and then the radial flow cannot take place.

2.1.5 Drainage Resistance D_R

(Stuyt, 2005) mentioned that the relationship between head loss and corresponding resistance is given by:

$$h = qLR \quad (11)$$

Where h = difference in head (m); L = drain spacing (m); q = specific discharge (m/d); R = resistance (d/m).

The drainage resistance to flow can be expressed as:

$$D_R = \frac{h}{q} \quad (12)$$

Where D_R= drainage resistance to flow (day); h= the total head loss due to flow from the soil to drain (m); q= the drainage discharge (m/day). A system with low drainage resistance value is able to cope with higher recharges and/or maintain lower watertable levels than a system of a high drainage resistance value. The drainage resistance D_R may be expressed as a resistance to vertical flow D_{RV} and a resistance to horizontal flow D_{RH}.

$$D_R = D_{RV} + D_{RH} \quad (13)$$

The vertical drainage resistance D_{RV} is happened due to cracking and non-cracking areas and it can be written by substituting equation (5) as:

$$D_{RV} = \frac{h_V}{q} = \frac{d_{cr}}{K_{cr}} + \frac{H}{K} \quad (14)$$

The horizontal drainage resistance D_{RH} can be written according equation (10) as:

$$D_{RH} = \frac{h_h}{q} = \frac{L^2}{8K_{cr}d_{cr} + 8Kd_e} \quad (15)$$

The drainage resistance D_R can be written according equations (13), (14) and (15) as:

$$D_R = \frac{d_{cr}}{K_{cr}} + \frac{H}{K} + \frac{L^2}{8K_{cr}d_{cr} + 8Kd_e} \quad (16)$$

The drainage discharge (q) is function in the change of watertable head with the time and drainable porosity according to equation (3). Also it is function of drainage resistance. It can be expressed as:

$$q = \frac{h}{D_R} = -\mu\frac{dh}{dt} \quad (17)$$

By integration, according to the boundary conditions, the watertable head (h) decreased from ground surface (W=d_{cr}+H) initially at (t=0) to (h_t) after time (t).

$$-\int_{d_{cr}+H}^{h_t} \frac{dh}{h} = \int_{t_0}^{t} \frac{dt}{\mu D_R} \quad (18)$$

The head loss (h_t) after time (t) is:

$$\frac{h_t}{d_{cr} + H} = Exp(\frac{-\Delta t}{\mu D_R}) \quad (19)$$

The drainage rate (q_t) after time (t) is:

$$q_t = \frac{h_t}{D_R} = (\frac{d_{cr} + H}{D_R}) * Exp(\frac{-\Delta t}{\mu D_R}) \quad (20)$$

According to the boundary conditions at t=0, the original watertable head (h_0) is:

$$h_0 = W = d_{cr} + H \quad (21)$$

From equation (20), the original drainage rate (q_0) at t=0 is:

$$q_0 = \frac{d_{cr} + H}{D_R} \quad (22)$$

From equations (19), (20), (21) and (22), the recession equation can be written as:

$$\frac{h_t}{h_0} = \frac{q_t}{q_0} = Exp(\frac{-\Delta t}{\mu D_R}) \quad (23)$$

The recession equation for watertable drawdown can be written as:

$$h_t = h_0 e^{-\alpha} \quad \text{Where } \alpha = \left(\frac{\Delta t}{\mu D_R}\right) \tag{24}$$

From equation (23), the drainage resistance D_R can be expressed as a function of watertable head drawdown, time and drainable porosity as:

$$D_R = \frac{\Delta t}{\mu Ln\left(\frac{h_t}{h_0}\right)^{-1}} \tag{25}$$

Equating equations (16) and (25) is given:

$$D_R = \frac{d_{cr}}{K_{cr}} + \frac{H}{K} + \frac{L^2}{8K_{cr}d_{cr} + 8Kd_e} = \frac{\Delta t}{\mu Ln\left(\frac{h_t}{h_0}\right)^{-1}} \tag{26}$$

Then the drain spacing can be given as:

$$L^2 = \left[\frac{\Delta t}{\mu Ln\left(\frac{h_0}{h_t}\right)} - \frac{d_{cr}}{K_{cr}} - \frac{H}{K}\right]\left[8K_{cr}d_{cr} + 8Kd_e\right] \tag{27}$$

It can be noticed that the drain spacing (L) is influenced by the watertable head fluctuation (h_0/h_t) in time (t), average drainable pore space (μ) and the transmisivity of cracking top layer ($K_{cr}d_{cr}$) and sub-layer (Kd_e).

2.2 Drainage criteria

2.2.1 Agricultural drainage criteria

- The maximum permissible height of the water table is 1 m below the soil surface; and
- Irrigation water is applied every 14 days, and the field application losses percolating to the water table are 24 mm each irrigation.

2.2.2 Technical design criteria

- Drains are installed at a depth of 1.5 m; and
- PVC drain pipes with a radius of 0.04 m are used.

2.2.3 Soil data

- The depth of the impervious layer is 5.0 m below the soil surface; and
- The drainable porosity is 0.06.

3. Results

Assuming that the field application losses can be regarded as an instantaneous recharge, $R_i = 0.24$ m, the rise of the water table computed as:

$\Delta h = R_i/\mu = 0.24/0.06 = 0.40$ m (It is the current Egyptian drainage criterion in clay soil)

Assuming that, after irrigation, the water table rose to its maximum permissible height, then:

$h_0 = 1.5 - 1.0 = 0.5$ m

Thus, the following data are applied:

$K_{cr} = 0.5$ m/day, $K_b = 0.05$ m/day, μ = 6%, H= (5.0 – 1.5) = 3.5 m, de =1.65 m at $r_0 = 0.04$ m, $h_0 = 0.50$ m, $h_{14} = 0.1$ m, and t = 14 days

Substituting the above values into the new proposed equation (27) and the Glover-Dumm drainage equation:

$$L = \left(\frac{K d_e t}{\mu}\right)^{\frac{1}{2}} \left(ln 1.16 \frac{h_0}{h_t}\right)^{-\frac{1}{2}} \tag{28}$$

The drain spacing comparison between the two equations for different hydraulic conductivity (K) is shown in Figure 4. The new equation has top-cracking layer (K_{cr}) permeability ten times more than that of bottom layer (K_b). The homogenous (K) value in Glover-Dumm equation (28) is equal to bottom layer (K_b) in equation (27).

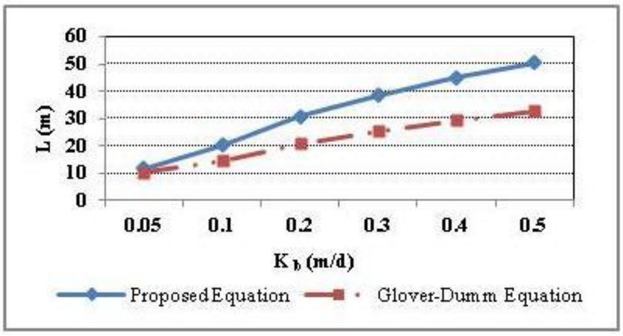

Fig. 4 Relation between drain spacing and hydraulic conductivity

The effect of crack depth (d_{cr}) on the drain spacing (L) for different hydraulic conductivity values (k_b) is shown in Figure 5. It is assumed that a soil profile has top-cracking layer of permeability (K_{cr}) ten times that of a lower bottom layer (k_b).

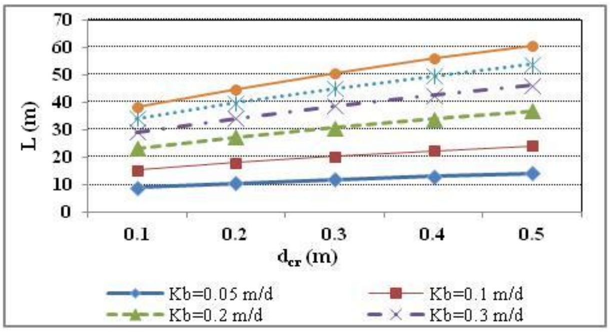

Fig. 5 Effect of crack depth and hydraulic conductivity on drain spacing in equation (27)

The effect of hydraulic conductivity ratio and the crack depth on drain spacing in equation (27) at K_b=0.1 m/d is shown in Figure (6).

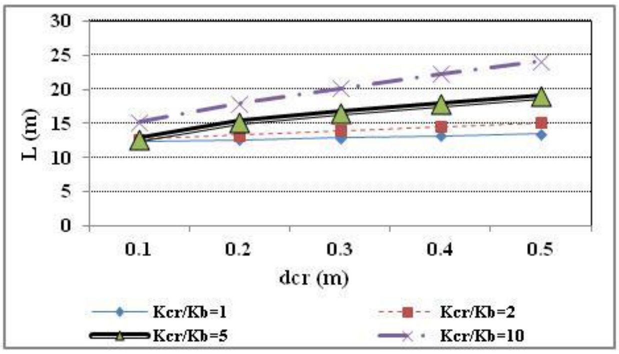

Fig. 6 Effect of crack depth and hydraulic conductivity ratio on drain spacing in equation (27) for (K_b=0.1 m/d)

4. Discussion

Although the obtained analytical transient solution in equation (27) is not tested against field data but it can be compared with other drainage equations such as Glover-Dumm for un-steady state condition. According to this solution the recession of the watertable from ground level immediately after irrigation to the desired watertable level within the equilibrium time is controlled by transmissivity of cracking layer and sub-layer and the average drainable pore space of the soil profile. In Figure (4), it is assumed that a soil profile has top-cracking layer of permeability ten times that of a lower bottom layer. The effect of cracks of top layer on drain spacing of new proposed equation (27) compared with the Glover-Dumm equation is obvious. At low hydraulic conductivity of 0.05 m/d, the drain spacing is approximately equal in both equations. As the hydraulic conductivity of soil bottom layer increases the gap between the two equations increases for drain spacing. The drain spacing (L) of Glover-Dumm equation, according to the design criteria, varies between 15 m and 33 m for different (K_b) values varies between 0.10 and 0.50 m/day while with the new proposed equation (27), it varies between 20 and 50 m. It can be concluded that the spacing computed by the new equation is wider with percentage varies between 38 % and 54%.

The effect of different values of bottom layer hydraulic conductivity on drain spacing is shown in Figure (5). The deeper the crack depth the wider is the spacing. The drain spacing increases due to the increase of hydraulic conductivity and crack depth.

The effect of hydraulic conductivity of cracking top layer on drain spacing is obvious. There is no effect on drain spacing for homogenous cracking soil (K_{cr}/K_b=1). The drain spacing increases as the hydraulic conductivity ratio increases as shown in Figure (6). The ratio (K_{cr}/K_b=10) has wider drain spacing than the ratio (K_{cr}/K_b=1) by 150% approximately.

Conclusions

The effect of cracking depth on drainage of heavy clay soils has been considered in the developed drainage design equation for subsurface field drains. It takes into consideration the influence of cracking top layer as well as bottom layer and the drainable pore space on the drainage of the soil profile. The proposed equation has been compared with the Glover-Dumm equation of unsteady state condition. The drain spacing computed by the new equation calculates wider spacing with percentage varies between 38 % and 54% according to crack depth. In the homogenous cracking soil (K_{cr}/K_b=1), the crack depth has no effect on drain spacing. The ratio (K_{cr}/K_b=10) has wider drain spacing than the ratio (K_{cr}/K_b=1) by 150% approximately in the proposed drainage equation.

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