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SPACING OF CURTAIN DRAINS ON SLOPING LAND FOR ON-SITE SOIL ABSORPTION SYSTEM

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A variety of methods are available for treating and disposing of wastewater. The selected method for treatment and disposal depends upon the site conditions, the cost of construction, and system maintenance. The ultimate goal of any wastewater treatment and disposal facility is to produce an effluent which is not harmful to the environment. Cooper and Rezek (1977) reported that in 1970, about 16.6 million housing units in U.S.A. disposed of their domestic waste through septic tank-soil absorption system. Most of these systems depended upon subsurface infiltration fields for ultimate disposal of their wastewater.

The conventional system of on-site disposal and treatment of liquid domestic waste consists of a septic tank and subsurface soil disposal system. Successful operation of an on-site septic tank-soil absorption system depends greatly on the hydraulic conductivity of the soil and a variety of other factors such as groundwater table location, depth to impermeable layer or bed rock and slope. Unsatisfactory performance of the system is evidenced by either surface seepage of untreated effluent or by contamination of groundwater due to inadequate soil purification of septic tank effluent.

Sites with high water tables are considered unsuitable for on-site soil absorptive systems (Troyan and Morris, 1977). A method for establishing an on-site septic tank-soil absorption system in areas of high water table is to lower the water table by a system of parallel drains. A minimum of 90 cm of unsaturated flow thickness between the bottom of the seepage bed and water table is necessary for effective purification of wastewater (Tyler, et al. 1977). Decoster (1976) has shown that a simple design incorporating the hydrologic properties of the soil will give necessary drain length and depth for adequate effluent purification on level sites.

The objectives of this study were: (1) to characterize the steady state water table in a moderately sloping aquifer with a seepage bed placed between nonrecharged areas within parallel curtain drains, (2) to use the resulting mathematical model to determine the drain depths necessary to maintain the water table at a required depth below the bottom of the seepage bed.

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Mathematical Formulation

A number of scientists have studied the problems of free surface groundwater table on sloping land. The studies were based on the solution of linearized Boussinesq's equation. According to Werner (1957), Boussinesq's equation for unsteady free surface groundwater flow on moderately sloping land is

$$K\left(\frac{\partial^2 z}{\partial x^2} + \left(\frac{\partial z}{\partial x}\right)^2\right) - K\Theta\frac{\partial z}{\partial x} + \rho = \frac{\partial z}{\partial t} \qquad (1)$$

where K = hydraulic conductivity of the soil; ρ = rate of recharge to the water table; x = horizontal coordinate of length; z = height of water table above impermeable layer; t = time; Θ = slope of bottom of aquifer (impermeable barrier). Capillary effects are neglected (Fig. 1).

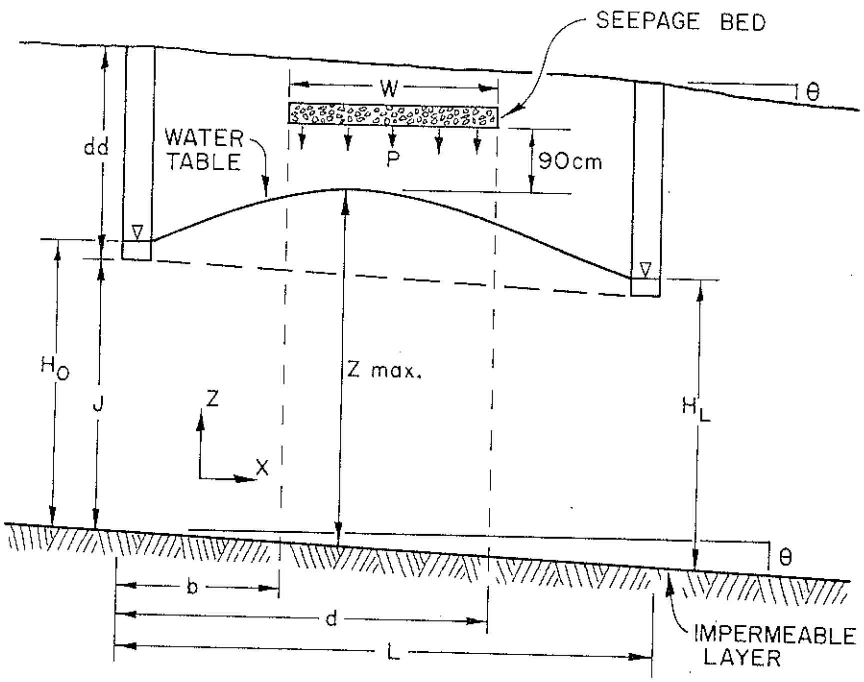

Fig. 1 Schematic Representation of Groundwater Table in Equilibrium with Recharge on Sloping Sites

The diagram shows that maximum water table height occurs under the seepage bed (section b and d). For effective treatment of effluent, it is necessary to leave at least 90 cm of unsaturated soil between the bottom of seepage bed and the highest point of the water table. The equation of the maximum point on the water table is (Okeke, 1980)

$$Z^2_{max} = (\gamma\psi + \omega)/\phi + \gamma\phi_e - \gamma \qquad (2)$$

Where $\gamma = P/a^2$

$\psi = e^{a(L-d)} - e^{a(L-b)} + e^{aL} - 1$

$\omega = H_0^2 e^{aL} - H_L^2 + (P/a)(d - be^{aL})$

$\phi = e^{aL} - 1$

$\phi_e = \log_e \left(\frac{\gamma(-\phi)}{\gamma(e^{-ab} - e^{a(L-d)}) + \frac{P}{a}(b-d) + H_L^2 - H_0^2}\right)$

$a = \theta/D*$

$P = 2\rho/K$

$D* = De + 0.984\ Hmax$

$De = J/(1 + J/L\ (\frac{8}{\pi}\log_e(J/r) - 3.4)$

for $0 \le J/L \le 0.3$

$= L/(\frac{8}{\pi}\log_e(\frac{L}{r}) - 1.15))$

for $J/L > 0.3$

r = radius of drain plus thickness of gravel envelope or 1/2 of width of drainage ditch

Log_e = natural logarithm

De = equivalent depth

Hmax = maximum height of water table above center line of drain spacing

J = thickness of saturated medium between bottom of drain and impermeable layer

The height Z_{max} is a function of the dimensionless recharge rate (P), seepage width (d-b), width of nonrecharge portions (b) and (L-d), drain spacing (L), sum of depth of water in the drain and thickness of the saturated layer below the drain bottom (H_0 and H_L), and the slope (θ) of the basin.

Application

Equation 2 sets the limits for the siting of on-site septic tank soil absorption system on sloping land.

When the effluent loading rate, curtain drain spacing and aquifer characteristics are known, one has to determine how deep the drains would be installed in order to lower the groundwater table to a desired height. The groundwater height then becomes a function of depth of installation of curtain drains.

$$Z_{max} = f(dd)$$

Where dd = depth to bottom of the drain

<u>Design Problem 1</u>: A septic system is to be installed in an area where the water table is at or near the ground surface. The impermeable layer is 500 cm below the ground surface and lies on a 10% slope. Installation of curtain drains is proposed. The width of the drain is 20 cm. The width of seepage bed is 600 cm and the desired curtain drain spacing is 1000 cm. The

soil is sandy loam and its saturated hydraulic conductivity is 80 cm/day and will be loaded at 3 cm/day. At what depth will the curtain drains be installed to maintain the steady state water table at least 90 cm below the bottom of the seepage bed (Fig. 2)?

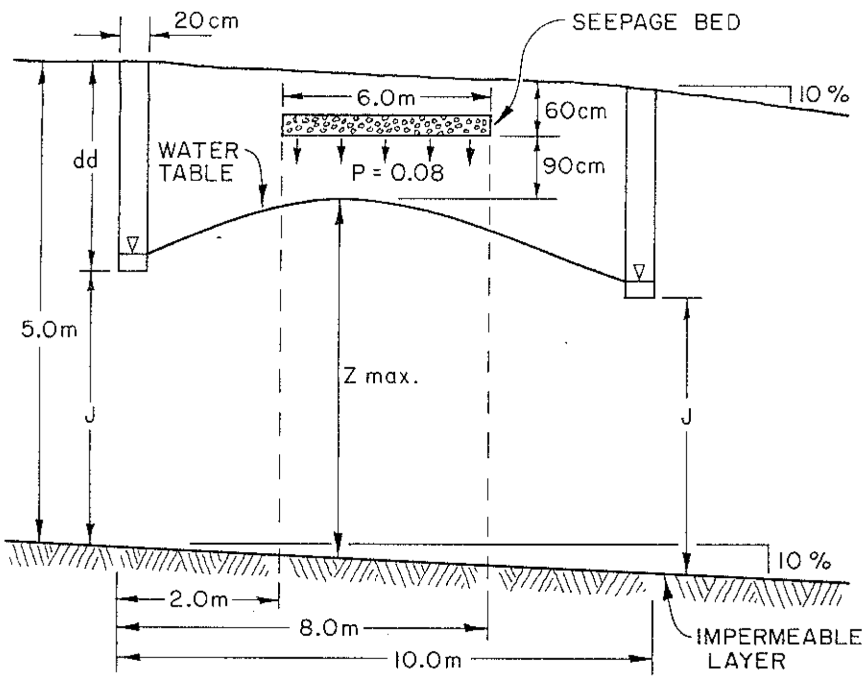

Fig. 2 Schematic Representation of Groundwater Table in Equilibrium with Recharge for Sandy Loam Soil (Example 1)

Solution: The recommended maximum loading rate for sandy loam soil is 3 cm/day (Otis, et al. 1977).

From equation 2 $P = \frac{2\rho}{K}$

$= \frac{(2)(3)\ \text{cm/day}}{80\ \text{cm/day}} = 0.075$

≈ 0.08

From figure 2 b = 200 cm

d = 200 cm + 600 cm

= 800 cm

If the bottom of seepage bed is situated 60 cm below the ground surface and if the water table is to be maintained at 90 cm below the bottom of seepage bed, then the problem is to find the drain depth that will keep the maximum water table height Z_{max} at 150 cm below the ground surface or 350 cm above the impermeable layer.

Assuming the drains are installed at 180 cm below the ground surface, then

J = 320 cm

since r = 10 cm

D* = 143.17 cm

and $a = 6.98 \times 10^{-4}$

From equation 2 Z_{max} = 333 cm

Therefore, with curtain drains installed at a depth of 180 cm, the maximum groundwater height will be 333 cm. This is 17 cm below the maximum allowable height of 350 cm above the impermeable layer. If the drains are installed further into the saturated system, for example 200 cm, then the maximum water table height will be approximately 314 cm. Table 1 contains solution of the above problem on 5%, 15% and 20% slopes for various drain depths.

Table 1. Water Table Height for Various Slopes and Curtains Drain Depth in Sandy Loam Soil*

Slope	dd - Drain Depth (cm)						
%	160	170	180	190	200	210	220
	Z_{max} - Maximum Height of Water Table (cm)						
5	352.1	342.5	332.8	323.2	313.7	304.1	294.6
10	352.0	342.4	332.8	323.2	313.6	304.1	294.5
15	351.9	342.3	332.7	323.1	313.5	304.0	294.5
20	351.7	342.1	332.5	322.9	313.4	303.9	294.4

*K = 80 cm/day, ρ = 3 cm/day and P = 0.08

The approximate drain depths and their corresponding maximum groundwater table heights on 5%, 10%, 15% and 20% slopes are given in Table 2 for a silt loam soil or a clay loam soil with saturated hydraulic conductivities of 20 cm/day and 10 cm/day and the recommended maximum loading rates of 2 cm/day and 1 cm/day respectively (Otis, et al, 1977).

Table 2. Water Table Heights for Various Slopes and Curtain Drain Depth in Silt Loam and Clay Loam Soils*

Slope	dd - Drain Depth (cm)						
%	160	170	180	190	200	210	220
	Z_{max} - Maximum Height of Water Table (cm)						
5	369.5	360.3	351.2	342.1	333.1	324.1	315.2
10	369.3	360.2	351.1	342.0	333.0	324.0	315.1
15	369.0	359.9	350.8	341.8	332.8	323.8	314.9
20	368.5	359.5	350.4	341.4	332.5	323.6	314.7

*Sandy loam soil has K = 20 cm/day, ρ = 2 cm/day and P = 0.2
Clay loam soil has K = 10/cm day, ρ = 1 cm/day and P = 0.2

An alternative method of solution is to assume a wide variety of installation depths and solve for the maximum groundwater height by plotting maximum groundwater heights against drain depths (Fig. 3). If the desired steady state maximum groundwater table height is 350 cm in sandy loam soil, curtain drains installed at any depth below 163 cm will be effective in maintaining the water table below the desired height. For the system on clay loam and silt loam soils, any depth greater than 182 cm below the ground surface will be quite appropriate.

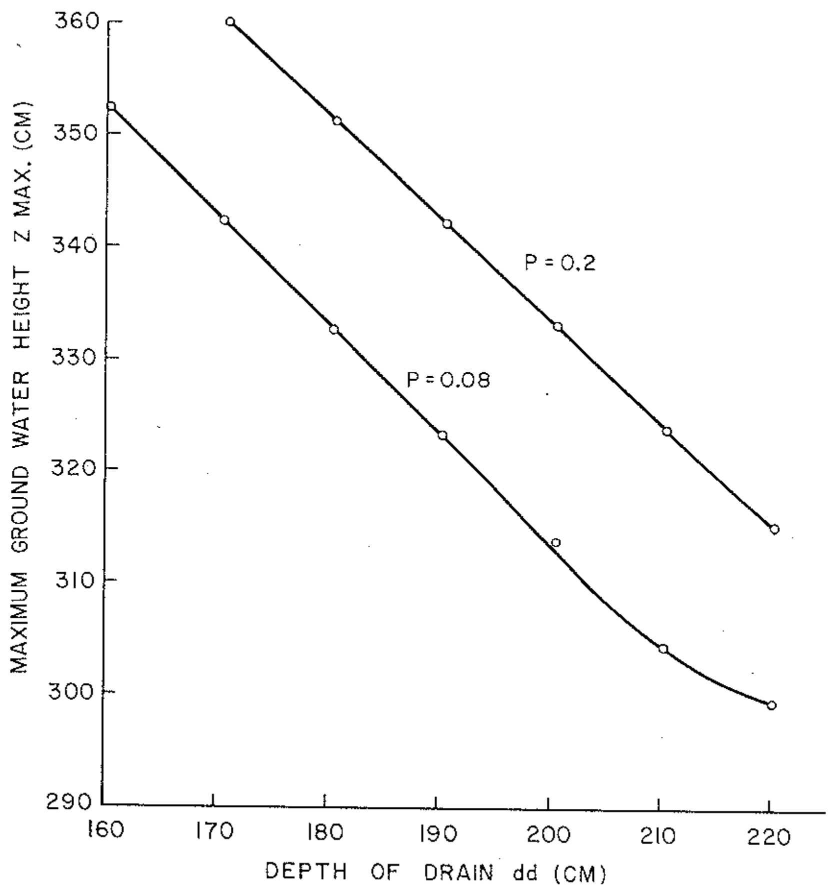

Fig. 3 Variation of Maximum Groundwater Table with Depth of Curtain Drain for Sandy Loam, Silt Loam and Clay Loam Soil

<u>Design Problem 2</u>: A saturated sandy loam soil is being considered for siting an on-site septic tank-soil absorptive system. The impermeable layer lies on a 10% slope and is 200 cm below the ground surface. The hydraulic conductivity is 80 cm/day. The proposed loading rate is 3 cm/day. Installation of curtain drains at 1000 cm apart is proposed and the width of the seepage bed is to be 600 cm. Is this site suitable for the proposed system (Fig. 4)?

<u>Solution</u>: Since the aquifer is shallow, the curtain drains will extend to the impermeable layer (Fig. 4). From the given data

$$P = \frac{(2)(3)\ \text{cm/day}}{80\ \text{cm/day}} \approx 0.08$$

$b = 200$ cm

$d = 800$ cm

$L = 1000$ cm

$dd = 200$ cm

$\theta = 10\%$

From equation 2 $\quad D^* = 49.2$ cm

$a = 2.03 \times 10^{-3}$

therefore $\quad Zmax = 89$ cm

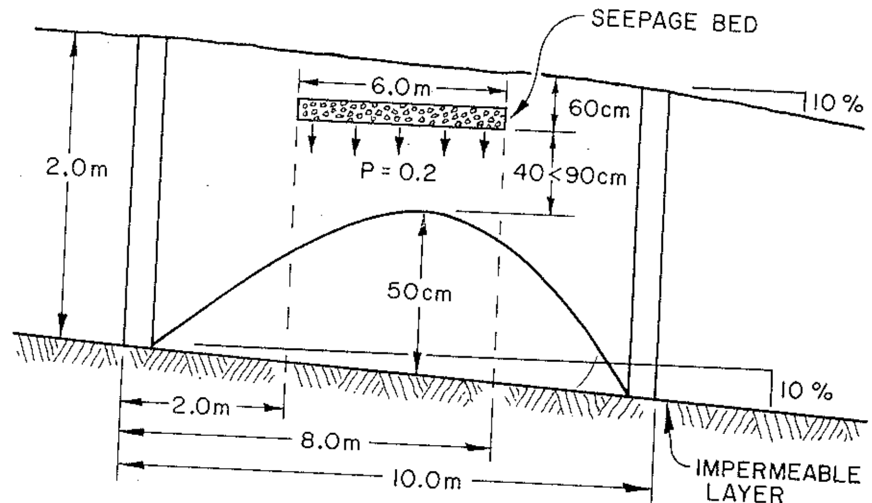

Fig. 4 Schematic Representation of Groundwater Table in Equilibrium with Recharge for Sandy Loam Soil Where Curtain Drain Extends to Impermeable Layer.

If the bottom of seepage bed is at 60 cm from the ground surface and 90 cm of unsaturated soil is allowed between the maximum water table height and bottom of seepage bed, the steady state maximum water table height is only at 50 cm above the impermeable layer. From the solution above, Zmax = 89 cm, which is higher than 50 cm. Therefore, the site cannot be used for on-site septic tank soil absorptive septic system.

If the same problem was solved for silt loam or clay loam soils having hydraulic conductivities of 20 cm/day and 10 cm/day respectively, with recommended maximum loading rates of 2 cm/day and 1 cm/day respectively, the resulting equilibrium maximum groundwater height (Zmax) will be 140 cm (Fig. 5). Therefore such a design should not be used. The maximum groundwater heights for the soil types considered on slopes of 5, 10, 15 and 20% are shown in Figure 5.

For shallow sites, such as that illustrated in this example, low recharge rates are necessary if groundwater heights are to be kept within desired limits.

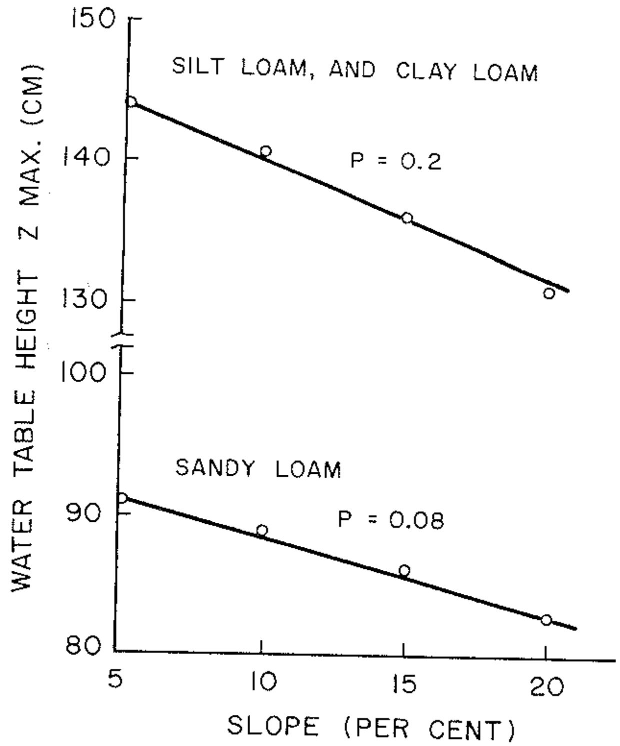

Fig. 5 Maximum Water Table Height with Slope of Land for Constant Recharge Rate for Sandy Loam, Silt Loam, and Clay Loam Soils with K = 80, 20, and 10 cm/day and ρ = 3, 2 and 1 cm/day, respectively.

Summary and Conclusion

The objectives of this study were to use analytical methods to characterize the steady state water table in a moderately sloping aquifer with a recharged bed placed within parallel curtain drains, and to demonstrate the methods of application in the establishment of on-site septic tank systems on moderately sloping land. The water table was characterized by Boussinesq's differential equation.

The drainage situations studied were for cases where drainage ditches do and do not penetrate aquifer completely.

An analytical solution was obtained by linearization of Boussinesq's equation and matching the boundaries of the recharge area with the nonrecharge sections to achieve continuity. The resulting equation of the phreatic line is nonlinear and the drain depth needed for any drainage configuration is obtained by iterative method.

Two cases were studied and the following conclusions were evident:

1. Water table height increases as the recharge rate increases for a given recharge width and slope of land.
2. Low recharge rates are necessary to be able to keep the water table within desired heights.
3. Slope has very little effect on maximum height of water table for the same recharge rate but slope has effect upon location of maximum water table height.

GLOSSARY OF SYMBOLS

θ = Slope of impermeable layer

b = Distance from upper drain to recharge section

K = Hydraulic conductivity of the soil

d = Distance from upper drain to end of recharge section

de = Equivalent depth of J

D* = Average depth

$a = \frac{\theta}{D^*}$, Reduced slope

dd = depth of curtain drain below surface

F(dd) = Function of drain depth

h = Depth of water in the drain

H_0, H_L = Depth of water from impermeable layer to the drainage ditch

H_{max} = Height of maximum watertable above drain spacing

J = Depth of water from bottom of ditch to impermeable layer

L = Length of drain spacing

Log_e = Natural logarithm

ρ = Rate of recharge to water table

$P = \frac{2\rho}{K}$, Dimensionless recharge to the water table

r = radius of drain plus thickness of gravel envelope of 1/2 of width of drainage ditch

t = Time (seconds)

x = Horizontal coordinate of length

Z = Height of water table above impermeable layer

Z_{max} = Maximum height of water table

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