SOME NOTES ON DRAINAGE DESIGN PROCEDURE

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Abstract

In these notes on drainage design procedure, three drain spacing formulae are considered suitable for designing sub-surface drainage systems. The Hooghoudt and the Kirkham-Toksöz formulae have been developed for steady state conditions and the Glover formula is applicable to the transient state condition. The steady state condition implies that the surface inflow is equal to the outflow through the drains and the water table remains static, whereas in the transient state the water table level changes with time. These formulae are mainly applicable to the design of tube drains, but Hooghoudt's formula can be used for designing open drains. The various formulae can be solved directly, but graphs have been included to simplify the solution of the different equations.

Sub-surface Drainage

This short article will deal mainly with the use of design formulae for planning sub-surface drainage. This form of drainage is frequently used to control the level of the ground water table in cultivated lands; although ground water control is applicable to other purposes as well, this article is confined to its agricultural application.

The three main functions of sub-surface drainage are—

(a) removal of excess ground water in the root zone of the crop plants during the growing season,

(b) maintaining the water table below ground level throughout the year, particularly in reclamation areas,

(c) reducing the levels of salinity and maintaining salinity levels in certain circumstances.

Some Misconceptions Regarding Drainage

Drainage is often thought of as a problem rather than as an integral part of irrigation design. In the past irrigation layouts were casually designed without any attention being given to the need for drainage. This was due to a number of factors, but mainly to an inadequate understanding of the basic procedures involved in drainage design. Economic factors accounted for many of the present problems. The cost of including drainage facilities in an irrigation scheme would increase the capital costs, while reference to drainage works would by implication suggest the existence of a problem—a feature that might put paid to the scheme. In fact, however, the cost of excluding drainage facilities in an irrigation project is courting disaster, however sound the design of the irrigation project. Furthermore, it will cost a great deal more to provide drainage at a later date, if in fact it is still possible to install drains.

A second misconception appears to be associated with applying drainage design functions. The various design functions have been developed from exact mathematical analysis, electric analog techniques (Vimoke and Taylor, 1962)[14] and various model analyses (Harding and Wood, 1942)[2] and they are universally applicable. Naturally, the variables have to be determined for local conditions, but this is not a difficult problem, provided the basic principles from which the formulae have been derived are fully understood.

A Review of Drainage Formulae

A great deal of research work has been carried out in developing the various drain-spacing formulae. Soil-water relationships have been extensively studied in the U.S.A. by Kirkham, van Schilfgaarde and Luthin; in the Netherlands by Hooghoudt, Ernst, Visser, Wind and others, and in Denmark by Engelund.

Drainage of large areas for various irrigation projects in the U.S.A. and in Australia, and the perennial drainage problems encountered in Holland, have made it necessary for economic design factors to be developed for drainage work. The relationship of the depth of the drain to the spacing naturally must have economic implications, as has the depth at which the water table must be maintained for successful plant growth and for the prevention of surface accumulation of salts. Both these aspects are of concern in relation to crop production in this country.

Some Basic Concepts of Groundwater Movement into Drains

A number of basic concepts have to be considered before the actual formulations are discussed.

Firstly, the two basic ideas of water movement into drains need to be stated. These are:

(a) *Steady state conditions*

In the steady state condition, it is assumed that the hydraulic head does not vary with time. It is also assumed that the height of the water table is static when water is applied to the surface and that flow into the drains is equal to the amount of irrigation or rain water flowing through the soil surface.

(b) *Transient state conditions*

In this state, it is assumed that the hydraulic head varies with time.

It is assumed that the water that has saturated the soil profile will continue to flow into the drains at a constant rate as the water table falls from one level to the other.

Hooghoudt (1940)[3] has developed formulations for the steady state condition based on the Dupuit-Forchheimer assumption, which is used to simplify the mathematical analysis in the development of the spacing equations.

Kirkham (1949)[4] has also developed similar equations for steady state conditions.

Glover (as reported by Dumm, 1954)[1] developed an equation for the transient state condition.

Secondly, there are two soil conditions to be considered:

(*a*) *Isotropic soils*

A soil may be isotropic if the texture does not vary to any great extent throughout the profile. Furthermore the hydraulic conductivity does not vary throughout the profile, that is the vertical hydraulic conductivity is equal to the horizontal conductivity.

(*b*) *Anisotropic soils*

Anisotropic soils are generally considered to be "micro-layered", but for drainage work the feature of importance is that the vertical conductivity is not equal to the horizontal conductivity.

(c) *Depth to impervious layer*

Soils are further classed as "infinitely" deep or of "finite" depth. The limits may be an impervious rock layer or a layer of clay. If a clay layer is present, it will be defined as impervious, provided the hydraulic conductivity is less than one-tenth of the conductivity of the layers above it. The depth to an impervious layer is particularly important as it has a very definite bearing on the spacing and performance of a drainage system.

Topographic Considerations

Drainage is usually employed on fairly level land, but in certain circumstances it may be necessary to drain sloping land. When this happens one can run into difficulty with drain-spacing formulae.

These formulae cannot be applied to determine the correct depth or spacing when drains are run along the contour. They apply only to spaced drains which run down the slope, at a gradient sufficient to convey the water at design velocities. Work is therefore being carried out in the U.S.A. to develop suitable formulations based on model studies applicable to sloping land. Luthin and Schmidt (1967)[7] have developed a formula, but it is accurate only for slopes up to about 10% and further model studies are being carried out to develop a suitable formula for sloping lands greater than 10%.

Drainage Formulae

Formulae for the solution of drain spacings based on the two flow assumptions have been developed by eminent scientists in a number of countries.

Formulations based on the steady state condition will be considered first, followed by details for transient flow condition.

Steady State Flow

Two formulations will be given, namely Hooghoudt's (1940)[3] and Kirkham and Toksöz's (1961)[6] formulae.

Hooghoudt's Formula

In the first instance, the soils are assumed to be homogeneous, isotropic, of known hydraulic conductivity and known depth to the impervious layer.

Fig. 1 shows the various dimensions given in the formula. In developing the formula, it was assumed that the surface inflow rate, from irrigation or rainfall, is equal to the inflow to the drain.

The formula for homogeneous soils is:

$$S^2 = \frac{4k(H^2 - h^2 + 2dH - 2dh)}{V} \quad \ldots\ldots\ldots\ldots (1)$$

and when the drain is empty, then equation (1) reduces to—

$$S^2 = \frac{4KH\,(2d + H)}{V} \quad \ldots\ldots\ldots\ldots (2)$$

In the case of multilayered soils where the hydraulic conductivity varies from layer to layer, then the following equation may be used (Fig. 1):

$$S^2 = \frac{8k_2dh}{V} + \frac{4k_1H^2}{V}$$

or equation (2) can be used if the weighted mean of the k value is determined as follows:

$$\bar{k} = \frac{k_1L + k_2L + k_3L}{\Sigma L}$$

where,

$\bar{k}$ = the apparent hydraulic conductivity
ΣL = sum of the thickness of the layers
L = the "thickness" of the layers in which k value is measured
k = the k value of each layer.

The variables shown in the diagram also apply to equation (1) and (2)

S = the spacing between the drains
K = hydraulic conductivity
H = the height of the water table midway between the drains
h = the depth of water above the bottom of the drain, in the case of open drains
d = the depth from the drains to the impervious layer or the equivalent depth from the graphs, where the impervious layer is at great depth
v = drainage coefficient.

These formulae are based on the assumption that the impermeable layer is not located at great depth below the drain line, where it is the "d" value needs to be corrected to yield the equivalent depth as shown in Fig. 2.

Kirkham-Toksöz Formula

The Kirkham-Toksöz (1961)[6] formula is based on exact mathematical procedure and has been tested in the field. This formula is suitable for application to steady state conditions where the groundwater recharge is from surface or artesian sources. (See equation below.)

In the case of soils of finite depth—

$$H=2S\frac{v}{k}\cdot\frac{1}{1-\frac{v}{k}}\cdot\frac{1}{\pi}\left\{\ln.\frac{2S}{r}+\sum_{m=1}^{\infty}\frac{1}{m}\left(\cos\frac{m\pi r}{s}-\cos m\pi\right)\left(\cot h\frac{m\pi h}{s}-1\right)\right\}$$

where: h, v, k and s are the same as in the previous equations, but "r" is the radius of the drain tube.

For soil of infinite depth

$$H=2S\cdot\frac{v}{k}\cdot\frac{=1}{1-\frac{v}{k}}\frac{1}{\pi}\cdot\ln\frac{2S}{\pi r}$$

The graphic solution of these two formulae are given in Fig. 3 (a) and (b).

The Kirkham and Toksöz[6] and Hooghoudt[3] equations do not differ by more than 5% and may be used to determine drain spacing for most steady state conditions. There is, however, one proviso governing their use, namely that the drain lines must not be located on the impervious layer, but above it.

The Transient Flow Condition

The Glover formula (as reported by Dumm)[1] is used extensively in the U.S.A. for drainage design in irrigation areas. The formula has been derived from the heat flow equation in solids. It is used to determine drain spacing when the water table is initially at one level and then falls slowly to another lower level during a given time period.

The general conditions and dimensions for the formula are given in Fig. 4 (a) and (b).

The formulae are given by the following equations—

$$\frac{y}{yo}<0.8$$

where y = required height of the water table above the drain line

and yo = initial height of water table

$y = yo\,.\,1.16^{-t/j}$

where t = time which is required to lower yo to y in days

and $j = \frac{v\,S^2}{10K\;D}$

where j = "reservoir coefficient"

and $D = d + \frac{yo+y}{4}$ or $= d + \frac{y}{2}$

where D = average depth of flow

d = distance from drain to impervious layer

then $S^2 = \frac{10kDt}{v\ln(1.16\,yo/y)}$

where S = Drain spacing

k = hydraulic conductivity of the soils

v = specific yield (%) or drainable porosity, which can be estimated from the following relation

v = k expressed as a decimal, e.g. k = 4

Therefore v = 4 = 2% or 0.02.

In these formulae the units employed can be expressed in either feet or in the metric system. In the graphs measurements are given in feet. The formulae are best solved by using the two graphs given in Fig. 4 (a) and (b). If the graphs are used a successive procedure is adopted for determining the correct value of "S" and "t", assuming that all the other values are known.

The flow equations from these formulae are respectively—

(a) for drains located above an impermeable layer

$$q=\frac{2\,kyD}{S}$$

where q = flow in cubic feet/foot/day and k, y, D and S have the same notation as for the previous equations.

(b) for drains located on an impermeable layer

$$q=\frac{4k\,yo^2}{S}$$ - cubic feet/foot day

Limitations of the Formulae

It must be stressed that to fully appreciate the application of these formulae, their derivations should be studied in the original papers (References 1, 3, 4, 6 and 8). Further, it should be understood that the formulae were drawn up in relation to ideal conditions and become less accurate in extreme cases, where soils are more complex. Despite this the formulae have been tried in the field and found to be satisfactory. If the variables have been correctly assessed, they will be equally suitable for use in South Africa.

The formulae quoted are not suitable for determining drain spacing on land with slopes of more than 4 to 5%; on slopes steeper than this the flow characteristics become inaccurate. Research work is being carried out at present to provide data relevant to drain spacing on steep slopes (Luthin and Schmid (1964))[7].

Basic Factors in Drainage Formulae

There are a number of factors or variables that have to be correctly measured if the formulae are to be accurate.

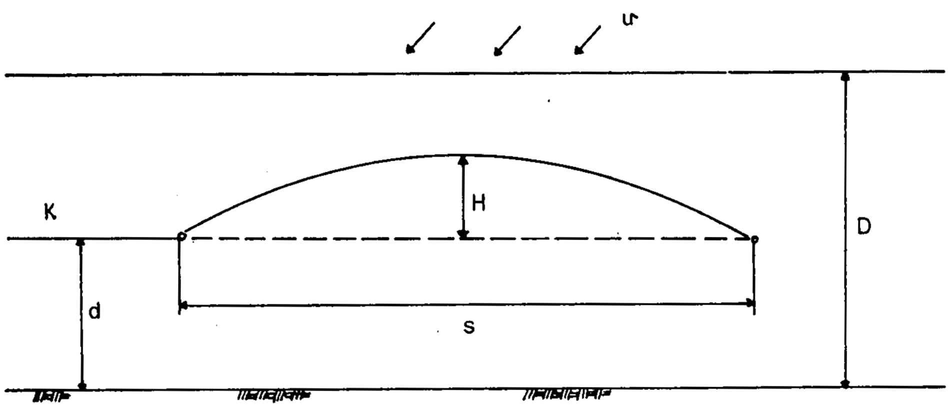
The Drainage Coefficient

The drainage coefficient "v" is the amount of water that moves into or can be removed from the soil by the drains, and is expressed as a volume per unit area per unit of time. It can be determined from rainfall, as in Europe (Hooghoudt, 1940)[2] or as a percentage of excess irrigation water (Maasland, 1956)[8]. In Holland a value of 7 mm/day is used as a drainage coefficient. In Australia, they use 1/64 acre foot/day (Maasland, 1957)[9].

In some irrigation projects, the drainage coefficient is expressed in terms of the leaching coefficient. This

Figure 1

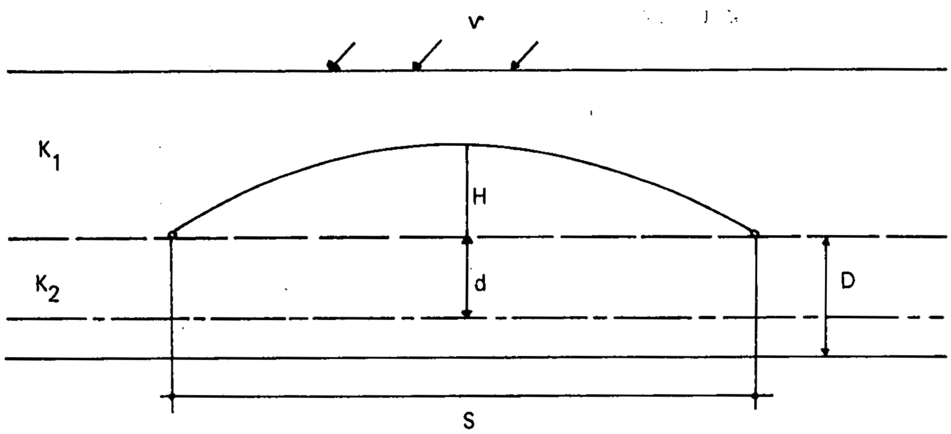
Hooghoudt's Formula



Use Formula 1 for open drains and Formula 2 for tube drains

$$S^2 = \frac{4k(H^2 - h^2 + 2dH - 2dh)}{v} \qquad 1$$

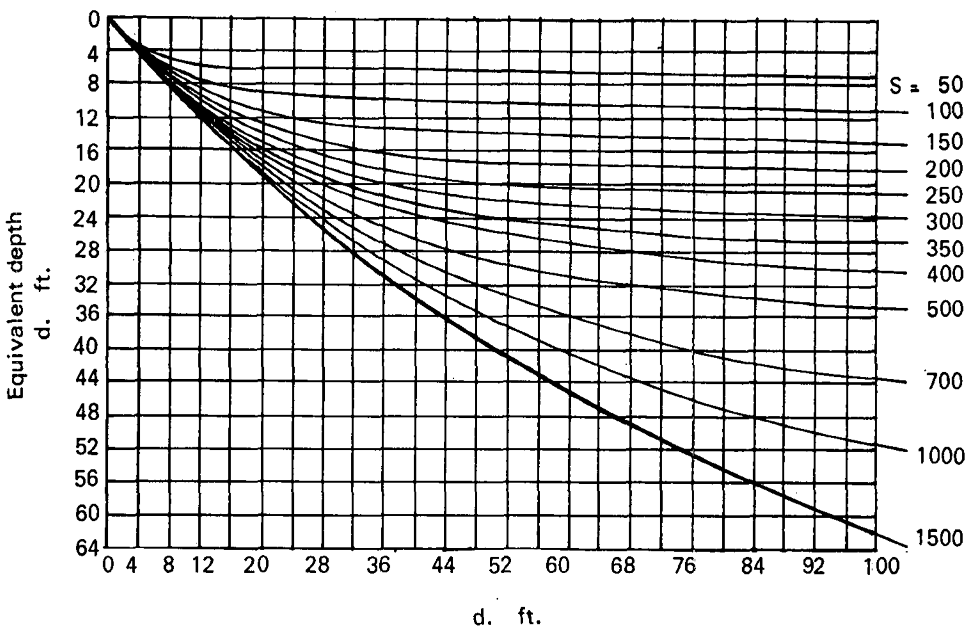
$$S^2 = \frac{4KH}{v}(2d + H) \qquad 2$$



Two Layered Soil using the following formula

$$S^2 = \frac{8k_2 dH}{v} + \frac{4k_1 H^2}{v}$$

Figure 2



Depth to Impermeable Layer

Depth Correction in Hooghoudt's Formula

is based on the salinity levels of the soil, drainage water and irrigation water, using the following equations:

$$\text{Diw} = \left(\frac{\text{EC dw}}{\text{EC dw} - \text{EC iw}}\right) \text{D ew}$$

where Diw = depth of irrigation water in inches
EC dw = electric conductivity of the drainage water in mmhos
EC iw = electric conductivity of the irrigation water in mmhos
D ew = depth of the crop water or consumptive use of the crops to be grown, in inches

$$\text{v} = \text{Ddw} = \frac{(\text{EC iw})}{(\text{EC dw})} \text{Diw}$$

where v = Drainage coefficient or depth of drainage water (Ddw).

The full explanation of the derivation of these formulae will be found in the references (U.S.D.A. Handbook)[12].

Detailed studies of crop water requirements and tolerances to waterlogging for various periods will be needed to determine the drainage coefficients for local conditions.

Drainage problems encountered in cane-growing areas in South Africa are frequently associated with irrigation schemes, the main objectives being the maintenance of a suitable salt balance in the soil. Other than this, drainage is important in reclaimed lowlands or vlei areas, where the drainage coefficient could be based on measurement of rainfall and the excess of irrigation water.

Depth of Drains

The depth at which the drain should be located below the soil surface depends on a number of factors. First, there is a relation between height of water table at the mid-point between the drains and their spacing. This relation can be determined by trial and error calculations, within the limits of possible drain depths.

Second, the depth of the drains may be limited by the type of drain used and the methods used in laying them. In Europe, flexible plastic tube drains have all but superseded the use of costly clay tiles. The great advantage of the flexible plastic drains is that they are laid by equipment similar in design to a mole-plough and this method of installing drains is only a quarter to a third of the cost of laying drains in open ditches. But the depth to which these machines can lay the drains is limited by the size of the machine and soil texture. Nevertheless, they are still cheaper than the traditional techniques. The larger machines work to depths of up to 5 ft while smaller equipment operates to a depth of 3½ ft. In fact, this is not really a serious limitation, but for smaller drainage projects the cost of equipment may not be justified.

Third, it may be necessary to maintain mid-point fluctuations of the water table at a specific depth. This will inevitably make it necessary to determine the optimum depth of the water table in relation to the capillary flux rates for maintaining salinity levels in the soil surface.

Depth of Water Table

The mid-point of the depth of the water table will depend on crop tolerance to saturated conditions in the root zone. Some plants can tolerate fairly long periods of saturation, others not; duration of saturation will vary with soil type and climatic conditions.

In Holland, Van Beers (1965)[13] gives a depth of 60 cm (24 inches) and Maasland (1957)[9] gives a figure of 1½ ft. as the figure used in Australia. Talsma (1963)[11] has studied the conditions under which salinization takes place in surface layers of the soil, and has related this to capillary flow rates. He has shown that the depth of the water table will depend on the flux rate of 0.1 cm/day and the depth is known as the "critical depth". Critical depth varies with the soil texture. Thus it is greater in the case of coarse-textured soils and less for fine-textured soils. The critical depth for a coarse-textured soil ranges from 200 to 600 cm, a medium-textured soil from 130 to 200 cm and a fine-textured clay from 50 to 100 cm.

The Hydraulic Conductivity

The hydraulic conductivity of the soil is the ability of the particular soil to transmit water through it, and it is the most important variable in the computation of drain spacings.

Hydraulic conductivity is measured in the field (laboratory permeability tests are valueless in design work) either in auger holes or in piezometers. If the water table is high enough an auger hole is driven to an appropriate depth and allowed to fill; when it reaches equilibrium with the water table the water is pumped out to a specified depth and the rate of refilling measured at equal time or distance rates (e.g. at 10-second or 30-second intervals measuring the rise in feet or cm).

These measurements are recorded and the hydraulic conductivity calculated from various equations (Kirkham (1955)[5], Maasland and Haskew (1957)[9], Hooghoudt (1940)[3]). The same method is applied in the case of piezometers. A piezometer measures the conductivity in some specific layer, whereas the auger hole measures the average conductivity of the soils through which it passes. The various methods used in taking these measurements, as well as the equations in their solution, will be found in the literature (Kirkham, 1955)[5].

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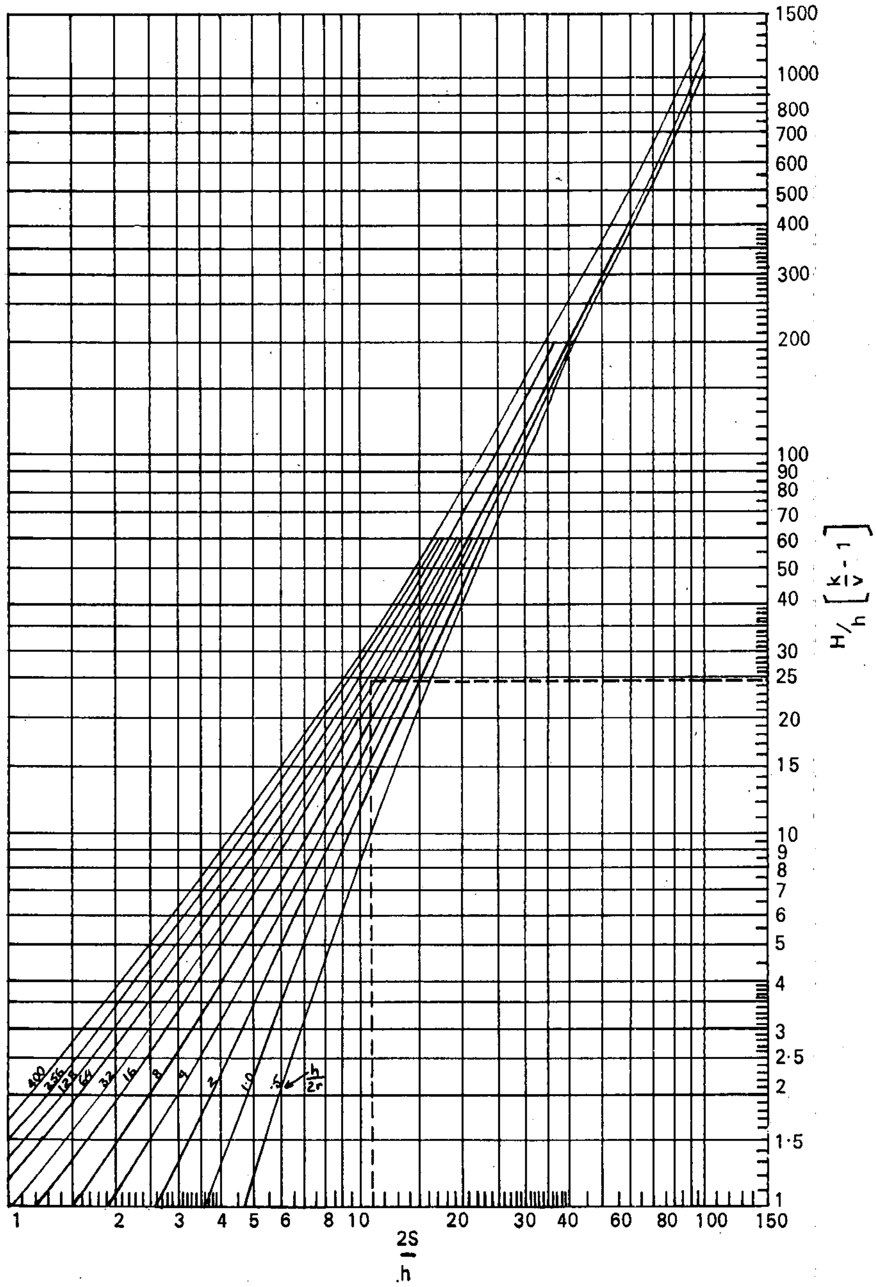
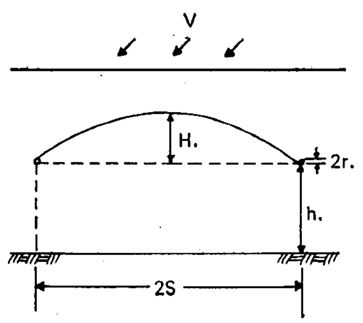
Figure 3 (a)

The Kirkham - Toksöz Formula
Drains at Finite depth





Example

$H = 1$ m. $2r = 0{\cdot}10$ m.

$h = 4$ m.

$K = 0{\cdot}5$ m/day

$V = 0{\cdot}005$ m/day.

$2S =$ unknown.

$\therefore \frac{h}{2r} = \frac{4{\cdot}0}{{\cdot}10} = 40$

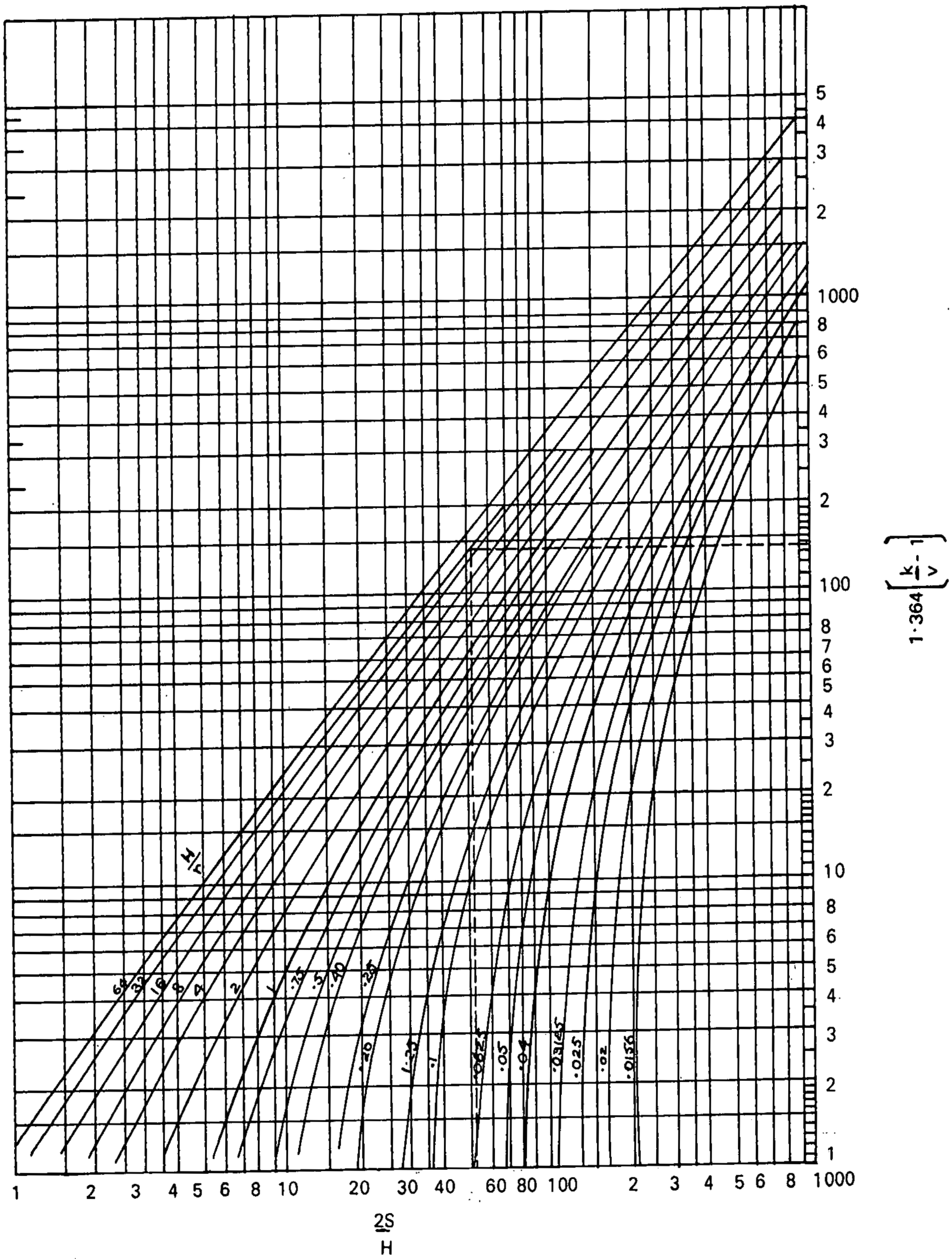
$H/h\left[\frac{k}{v} - 1\right] = \frac{1{\cdot}0}{4{\cdot}0}\left[\frac{{\cdot}5}{{\cdot}009} - 1\right] = 24{\cdot}75$

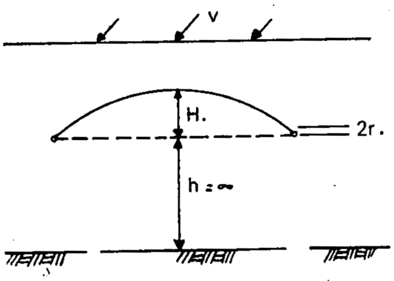
$\therefore \frac{2S}{h} = 10{\cdot}9$ & $2S = 43{\cdot}6$ m. or 143 ft.

After Kirkham & Toksöz 1961

Figure 3(b)

The Kirkham - Toksöz Formula
Drains at Infinite Depth.





After. Kirkham & Toksöz (1961).

Example

H = 1m
h = ∞
K = 0·5m.
v = 0·005m

2r = 0·10m.
∴ r = 0·05m

$\therefore \frac{H}{r} = \frac{1 \cdot 0}{\cdot 05} = 20$

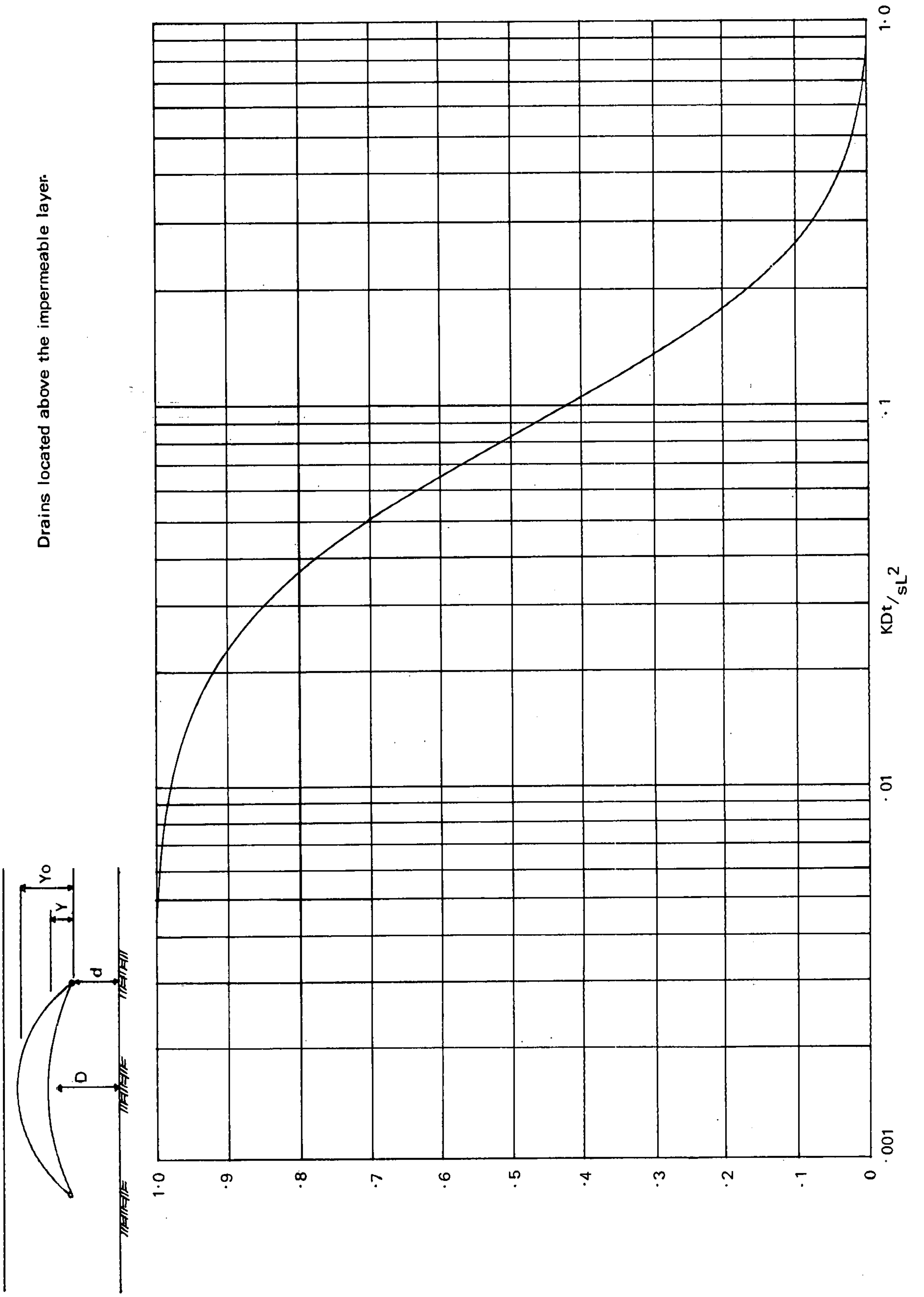
$\& \; 1 \cdot 364 \left[\frac{K}{v} - 1\right] = 1 \cdot 364 \left[\frac{\cdot 5}{\cdot 005} - 1\right]$

$= 135$

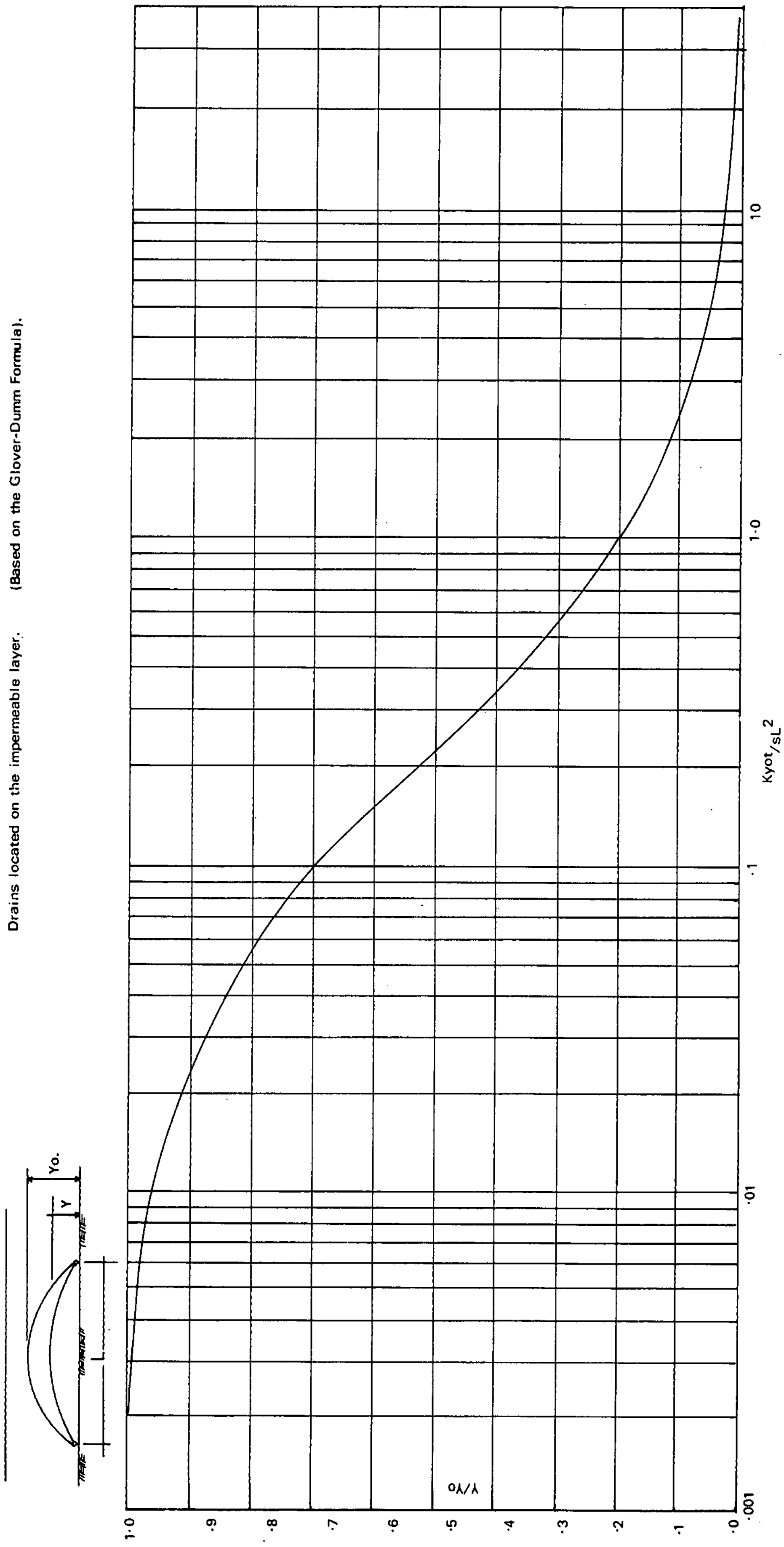
$\frac{2S}{H} = 52 \quad \therefore 2S = 52m.$

Figure 4(a)

The Transient Flow Formula



Transient Flow Formula. Figure 4 (b)



Discussion

Mr. Turck: These formulae appear to be designed for large areas of flat land. Would they work in the case of small areas, say five acres of undulating land?

Mr. Coles: The formula is merely the starting point for design. As regards areas of land, most of the work in connection with drain design development has been done in Holland where small areas are involved. The formulae could be used for determining the spacing for smaller areas of land; there is no limit. In the case of undulating land, the drain lines may be short and more collector drains would be required but the spacing would depend on the soil characteristics and the design constants used for the prevailing conditions, such as rainfall and crops.

Mr. Gosnell: In arid areas like the Rhodesian lowveld irrigation at a high rate has been applied to land which has been used to little rain and as a result drainage problems have occurred.

I was recently in the Murrimbiggee area which is one of the world's biggest irrigation schemes and there they are using these methods. Hydraulic conductivity is measured by the open auger hole method using the formula of Maasland and Haskew and the Hooghoudt drainage spacing formula is used to convert the hydraulic conductivity measurement to practical drain spacing. This has been working well for the past ten or so years over an area of about 50,000 acres.

All the drains are tiles.

Mr. Hansen: Does hydraulic conductivity take into account both the chemical composition of the soil and the particle size?

Mr. Coles: Hydraulic conductivity should not be confused with permeability.

Permeability is the property of a porous body alone and not of the fluid and it can be expressed as follows:

$$K^1 = \eta/\rho g \cdot K$$

where K^1 = intrinsic permeability (l^2)
η = viscosity
ρ = density of the fluid
g = gravity factor

Whereas, the hydraulic conductivity is expressed as:

$$K = K^1 \rho g/\eta$$

K = hydraulic conductivity (l/t)
l = Unit of length
t = unit of time.

The particle size does have a bearing on the rate of flow through the soil; the hydraulic conductivity of a coarse textured soil is greater than that for a fine soil.

The hydraulic conductivity of a soil is not constant as the interaction between soil and water constitutes a dynamic system and depends largely on the make-up of the soil particles. A soil containing montmorillonitic clay undergoes greater change on wetting and drying than other clays.

Soils that are high in exchangeable sodium tend to disperse and swell when leached with a water low in salt. The normal seasonal water fluctuations up and down the profile, as well as lateral water movement, would alter the hydraulic conductivity at various times, but the conductivity would remain constant within reasonable limits.

However, unless very great changes take place, the measured conductivity is accepted as being representative of that soil and can be used for design purposes.