THE AUGER HOLE METHOD

A field measurement of
the hydraulic conductivity of soil
below the water table

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1. INTRODUCTION

The auger-hole method is a rapid, simple and reliable method for measuring hydraulic conductivity of soil below a water table. It is mostly used in connection with the design of drainage systems in waterlogged land and in canal seepage investigations.
The method, originated by DISERENS (1934), was improved by HOOGHOUDT (1936) and later by KIRKHAM (1945, 1948), VAN BAVEL (1948), ERNST (1950), JOHNSON (1952) and KIRKHAM (1955).
The general principle is very simple: a hole is bored into the soil to a certain depth below the water table. When equilibrium is reached with the surrounding groundwater, a part of the water in the hole is removed. The water seeps into the hole again, and the rate at which the water rises in the hole is measured and then converted by a suitable formula to the hydraulic conductivity (k) for the soil.

The auger-hole method gives the average permeability of the soil layers extending from the water table to a small distance (a few decimetres) below the bottom of the hole. If there is an impermeable layer at the bottom of the hole, the value of k is governed by the soil layers above this impermeable layer. The radius of the column of soil of which the permeability is measured is about 30–50 cm.
The use of this method is limited to areas with a high groundwater table (at least during part of the year) and to soils where a cavity of known shape can be maintained throughout the test. Hence in certain sandy soils it is necessary to use a perforated tube (for description of the latter see Appendix No. II).

This treatment is mainly for practical purposes, so that the theory of the flow of water into an auger-hole has not been considered; only some background information is given, in order to make clear the reasons underlying the instructions and recommendations. The graphs and formulae given are largely based on Ernst's publication (1950), having the least limitations, especially as regards the quantity of water that has to be removed from the hole. Moreover, with the help of these graphs the k-value can be computed quickly and easily.

In measuring hydraulic conductivity in the field, four phases can be distinguished, each having its own problems:
- The drilling of the holes.
- The removal of the water from the hole.
- The measurement of the rate of rise.
- The computation of the hydraulic conductivity from the measurement data.

2. THE DRILLING OF THE HOLES

This has to be done with the minimum disturbance to the soil.

The *required depth* of the holes depends on the nature, thickness and sequence of soil layers in the area under investigation and on the depth at which it is required to determine hydraulic conductivity. If the soil is homogeneous to a great depth, a practical drilling depth will be about 60 to 70 cm below the water table, or preferably somewhat more than the length of the bailer.

In many cases, however, the profile consists of *two or more layers* having an appreciable difference in permeability. It will often be desirable to know the permeability of each layer. When using HOOGHOUDT's formula (1940) or similar formulae for designing a tile drainage system it is necessary to know the k-factor of the soil above and below the drains. If the water table lies well within the upper layer the hydraulic conductivity of each layer can be determined. In this case it will be necessary to work with *two or more holes* at different depths. The bottom of the shallow hole should be at least 10–15 cm above the lower layer and – for practical reasons – 20 cm below the water table. The deep hole, which for tile drainage design purposes normally has a depth of 2 meters, is drilled first and the various soil layers are examined and described. The depth of the shallow hole is determined on the basis of this profile investigation.

If a very high hydraulic conductivity can be expected and the soil is comparatively homogeneous, a hole at a slight depth – 30 to 50 cm below the water table – will be best, in view of the short time available for taking reliable measurements (see Appendix No. I).

Fig. 1.

Despite of the fact that the tested soil column associated with the auger-hole method is much larger than an undisturbed core sample taken for laboratory tests (1400 : 1, REEVE and KIRKHAM, 1951), it will be necessary to repeat the permeability determinations *at several places*, because of the differences which always occur in permeability of soils classified as one soil type. For detailed tile-drainage investigations one determination to every two acres will usually be sufficient.

One man can drill about 10–20 sets of holes a day. The auger used in the Netherlands (an open blade type, see fig. 1) is very suitable for use in wet clay soils. The closed type posthole auger commonly used in the USA is excellent in dry soils, but is less suitable for wet clay soils (Soil Survey Manual, U.S.D.A., 1951, page 67).

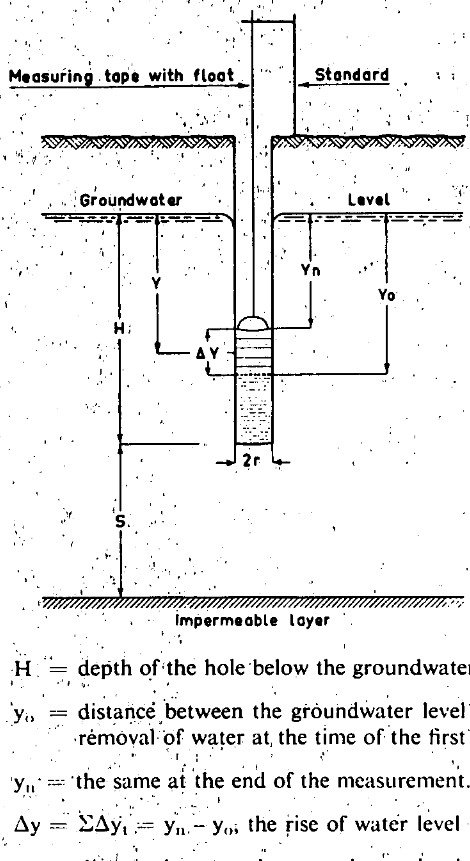


Fig. 2. Diagram of method followed in determining the hydraulic conductivity by the auger-hole procedure.

H = depth of the hole below the groundwater table.

y_0 = distance between the groundwater level and the elevation of the water surface in the hole after removal of water at the time of the first reading.

y_n = the same at the end of the measurement. Usually about 5 readings are taken.

$\Delta y = \Sigma \Delta y_i = y_n - y_0$; the rise of water level in the hole during the time of measurement,

y = distance between the groundwater level and the *average* level of the water in the hole during the time of measurement.

$$y = \frac{y_n - y_0}{2} = y_0 - \tfrac{1}{2}\Delta y.$$

r = radius of the hole.

S = depth of the impermeable layer below the bottom of the hole.

Note: The measurements should be completed before $y_n < 3/4\ y_o$, or $\Delta y > 1/4\ y_o$.

3. THE REMOVAL OF WATER FROM THE HOLE

This can start when equilibrium with the surrounding groundwater is attained and the depth of the water table has been recorded. Usually it will take 10–30 minutes to refill the hole in a moderately permeable soil (k = 1 m/day), some hours in a slowly permeable soil (k = 0.10 m/day).[1]
The seeping of the groundwater into the hole will also re-open soil pores in the wall of the hole that may have been closed by the auger. If an open blade-type of auger is used, it is unnecessary to remove the water from the hole 2 or 3 times for this purpose.
The most effective way of removing the water is with a bailer, viz.: a thin-walled pipe of about 50 to 60 cm in length, with a diameter of about 2 cm less than the diameter of the auger-hole and with a valve at the bottom. This bailer can also be used in combination with a perforated tube for making a hole in the unstable sandy soils.
The water level in the hole should be reduced 20 to 40 cm (y_o = 20 – 40 cm, see fig. 2). One or two bailings are required – depending on the length and diameter of the bailer used. If the soil has a very low hydraulic conductivity, it will be better to bail at least 40 cm of water from the hole in order to increase the rate of rise; this will reduce the time required for taking a reliable measurement. For measuring high hydraulic conductivity values, a y_o of 20 cm is better. When using the graphs given in this paper there is no obligation to work with a nearly empty hole or one that is half full, as stated by JOHNSON (1952), ROE (1954) and U.S.D.A. (1954).

4. THE MEASUREMENT OF THE RATE OF RISE

4.1. INTERVAL AND RANGE

The measurement properly consists in determining the rate at which the water rises in the hole. The observations are made either with a constant time interval (Δt) or with fixed intervals for the rise of the water (Δy_t), depending on the equipment available. In order to increase the accuracy of the results and reduce the effect of irregularities some 5 readings are usually taken as the water level rises.

[1]) 1 m/day = 4.2 $cm^3 : cm^{-2} : hour^{-1}$ = 4.2 cm/hour = 1.16×10^{-3} cm/sec. = 1.16×10^{-5} m/sec. = = 1.6 inch/hour, etc. = 3.28 cub. feet/sq. feet/day = 24.5 US gallon/sq. ft./day.

If an electric device is used, a fixed Δy is chosen. If a float with a measuring tape is used, either Δy or Δt can be measured at regular intervals. However, several stopwatches are necessary for measuring with a fixed Δy, whereas if measuring is done at regular intervals of time it is sufficient to use one watch with a good second hand. The latter method of measuring is usually followed in the Netherlands.

The time interval (Δt) chosen depends on the permeability of the soil and is usually 5–10–15 or 30 seconds. A Δt is usually observed to be corresponding to a Δy of about one cm. For soils with a very low permeability ($k = 0.01$, $r = 4$, $\Delta y/\Delta t = \pm 0.01$ to 0.02 mm per second), a Δy of about 5 mm and a Δt of some minutes is a good combination. If the soil has a very high permeability ($k = 10$, $\Delta y/\Delta t =$ about 10 mm per second) an interval of 5 seconds is observed. It will be clear that for soils with a high permeability Δy greatly exceeds 1 cm and only one or two reliable readings can be taken. Two men are needed for an interval of 5 seconds, whereas 10 second intervals can easily be read and recorded by one man.

Due consideration should be given to the fact that *it is not permissible to continue the measurements for too long* since the funnel-shaped drawdown of the water table which develops about the top of the hole as the hole fills would become too large. This would result in a decrease of the actual H-value and consequently in a decrease of the rate of rise, and if the k-factor were computed from the original H-value this would give too low a value for k (see example No. 3).

Care should be taken to ensure that not more than about 25 percent of the volume of water removed from the hole has flowed back at the end of the measurements. In other words, the measurements should be completed before $y_n < 3/4\, y_o$ or, which is easier to calculate, before $\Delta y > 1/4\, y_o$. For instance: if 40 cm of water have been removed ($y_o = 40$) we may measure over a range of $1/4\, y_o = 10$ cm or up to $y_t = 30$ cm. If $y_o = 28$ the permissible range is 7 cm or up to $y_t = 21$, assuming that the time interval between the removal of the water and the beginning of the actual measurements is very short and only a matter of a few seconds.

If the drainable pore space is more than 10 percent and the diameter of the hole is rather small ($r = 4$ cm) it is possible to obtain reliable measurements over a larger range, for instance up to $1/3\, y_o$.

2.2 times more water is needed to fill a hole with a 6 cm radius than one with a 4 cm radius, so that – if the holes used have a large diameter ($r = 6$) – the range for reliable measurements is often smaller than $1/4\, y_o$.

From the graphs given for $r = 4$ and $r = 5$ cm (see chapter 5) it can easily be calculated which rate of rise ($\Delta y/\Delta t$) may be expected for various conditions, since $\Delta y/\Delta t = k/C$. The order of magnitude of the rate of rise in a hole with a radius of 4 cm will usually be 1–2 mm per second for a moderately permeable soil ($k = 1$ m/day), 0.01–0.02 mm for a very slowly permeable soil ($k = 0.01$) and some centimetres per second for a highly permeable soil ($k = 10$). It will be clear that in the case of a highly permeable and moderately permeable soil we should start the measurements as soon as possible after bailing, whereas in the case of a slowly permeable soil there is no reason to hurry. A calculation of the time available for reliable measurements is given in Appendix I.

4.2 EQUIPMENT

The equipment as originally used by HOOGHOUDT was fairly heavy and complicated (see HOOGHOUDT, 1936). Convenient electric equipment has been developed in the USA and is also used in Australia (MAASLAND, 1957). In the Netherlands convenient and simple equipment was developed by the late Professor M. F. Visser.

Fig. 3.

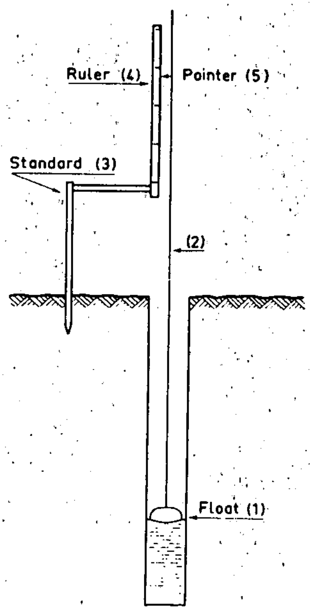


Fig. 3 demonstrates schematically this equipment. A 60 cm tube contains the various parts of the apparatus. This tube can easily be carried by hand. The bottom end of the tube is provided with a valve clack. By screwing a rod into the tube we get a bailer. The tube also contains a float (1) with a commercial type light-weight steel tape (2) and a standard (3), which is pressed into the ground and to which a ruler (4) is attached. The upper part of the ruler, which has a length of 40 cm, starts at zero. A pointer (5) attached to the steel tape moves along the ruler.

The latest simplification is that the ruler and the pointer have been omitted and the standard somewhat modified in order to prevent difficulties on windy days (fig. 4). The standard is pressed into the soil up to a certain mark so that the readings can be taken at a fixed distance (40 cm) above ground level.

Figure 5 shows the set used for the measurement of the hydraulic conductivity, complete with an auger with extension and a perforated metal tube.

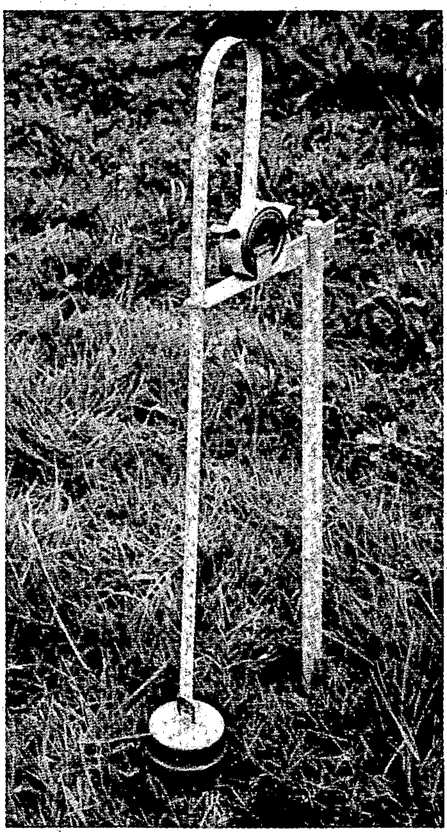


Fig. 4.

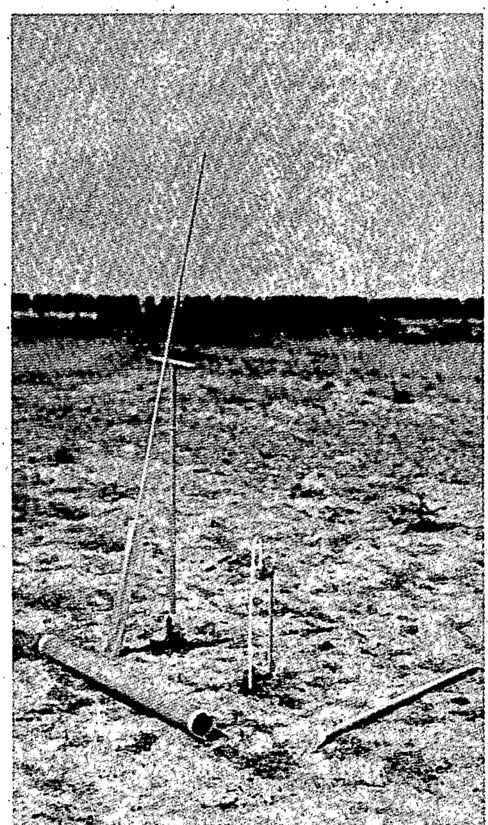


Fig. 5.

4.3 PROCEDURE

1. The standard is placed near the hole in such a way that the float and steel tape are exactly perpendicular above the hole.
2. The float is lowered to ground water level and this level is recorded.
3. The float is carefully hoisted from the hole and the standard turned sideways.
4. The water is bailed from the hole until the level is reduced by about 20–40 cm (this may take one or two bailings).

5. The standard is returned in its former position and the float placed on the surface of the water. The reading then has to be started as soon as possible.

6. About 5 readings are taken at regular intervals of time. Since it sometimes happens that the steel tape or float tends to stick to the wall of the cavity it is recommended to tap the steel tape regularly. All readings, including groundwater level and depth of the hole, are taken at the conductor of the tape on the standard (40 cm above groundlevel).

7. The depth of the hole is measured by use of the bailer or auger.

The rate of rise is sometimes measured immediately after the drilling of the hole. This method is time-saving and also has the advantage that no bailer is needed.
The level of the groundwater can usually be measured the same day, but if all layers have a very low permeability the groundwater level should be measured on the following day.
However, it should be noted that this method of measuring the rate of rise immediately after drilling can only be used in slowly permeable to moderately slowly permeable soils with little water in the hole after drilling (relatively large y_0), as the admissible amount of return flow during the time of drilling and measuring should be limited to about 25 percent of the amount of water removed by drilling. Moreover, the drilling has to be carried out with an open type of posthole auger, as this type gives less puddling along the wall of the cavity and the drilling proceeds more rapidly than with the closed type of posthole auger.

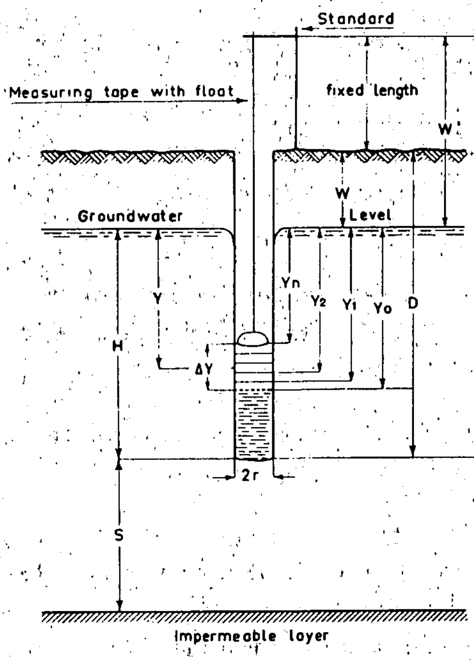


Fig. 6.

5. COMPUTING THE HYDRAULIC CONDUCTIVITY FROM THE DATA OF THE MEASUREMENTS

5.1. GRAPHS

The type of graph developed by BOUMANS (1953; VISSER, 1954) is commonly used in the Netherlands.

Recently other graphs as developed by WESTERHOF (ERNST, WESTERHOF, 1953) have also been used in combination with a special method of recording the readings for each interval of time. Using an additional mechanism on the standard, a pencil point is pressed at each interval of time on a slip of paper attached to the steel tape rule. This piece of paper is placed on a graph then and (in combination with a second graph) the k-factor can be computed. However, these graphs have only been prepared for $r = 4.5$ and $S > \frac{1}{2}H$.
ERNST (1950) prepared graphs for $r = 4$ and $r = 6$, both for $S = 0$ and $S > \frac{1}{2}H$. These graphs are the result of relaxation constructions.
The relation between the k-factor and the rate of rise ($\Delta y/\Delta t$) can be expressed as follows:

$$k = C \frac{\Delta y}{\Delta t} \tag{1}$$

The C value, in its turn is a function of y, H, r and S, which function can be read from the graphs.
Instead of computing the values of k for each Δy_t, these measurements may be averaged before evaluating C from the graphs, provided $\Sigma \Delta y_t < 1/4\ y_o$ and the consecutive readings are reasonably consistent.

Graph 1 ($S \geqslant \frac{1}{2}H$) and *graph* 2 ($S = 0$) – included in this bulletin – are for an auger-hole with a radius of *4 cm*. These graphs are the same as those prepared by ERNST (1950), except that a single logarithmic scale has been used instead of a double one in order to facilitate the reading.

Equation (1) can be solved by means of a nomogram as given on the left side of the graphs or by using a slide rule.

If $S < \frac{1}{2}H$ ($S = \infty$ gives about the same results as $S = \frac{1}{2}H$) no special equation or graph is available. Hence an estimate has to be made between the k-value for $S \geqslant \frac{1}{2}H$ and $S = 0$.
The difference between the C-values for $S \geqslant \frac{1}{2}H$ and $S = 0$ decreases with increasing H and if y is small in relation to H.

In general it can be said that the soil layers at a depth greater than 10–15 cm below the bottom of the hole have little influence on the rate of rise of the water in the hole, and the graph $S \geqslant \frac{1}{2}H$ can be used.

The graphs prepared by ERNST can also be used for an auger-hole with a radius other than 4 or 6 cm. Augers are often used, which have a radius of 5 cm or a 4-inch diameter. *Graphs 3 and 4*, included in this bulletin, have therefore been prepared for $r = 5$ *cm*. This has been done by converting the graphs for $r = 4$ cm. [1])

The graphs are used as follows:
C is read from the diagrams as a function of y and H. H is found at the abcissa in cm. Using the line with the proper y value, C can be read as the ordinate (see also example in graph 1).

5.2. FORMULAE

A formula is not often used for computing the hydraulic conductivity since convenient graphs are available. Moreover, unlike the formulae the graphs may be used for a wider range of y and H values and they are more accurate. The difference may amount to 20 percent. For the sake of completeness the formulae, which can be used when no graph is available, will be given here.

The following formula has been obtained for homogeneous soil with the impermeable layer at a certain depth, $S \geqslant \frac{1}{2}H$, below the bottom of the auger-hole (ERNST, 1950).

$$k = \frac{4000}{\left(\frac{H}{r} + 20\right)\left(2 - \frac{y}{H}\right)} \frac{r\,\Delta y}{y\,\Delta t} \qquad (2)$$

[1]) The easiest way of making this conversion is to multiply the values of H and y on the graph $r = 4$ by 5/4 or 1.25.

For instance: H_{20} on $r = 4 = 5/4 \times 20 = H_{25}$ on $r = 5$,
H_{30} on $r = 4 = 5/4 \times 30 = H_{37.5}$ on $r = 5$,
H_{40} on $r = 4 = 5/4 \times 40 = H_{50}$ on $r = 5$, etc.

The same applies to y.
To facilitate reading the values of H and especially of y, a new graph with regular intervals of $y = 20$, 25, 30, 35, etc., was constructed.
The values on the graph $r = 5$ for $y = 20$, 25, 30, 35, 40, 50, etc., are the same as the y-values 16, 20, 24, 28, 32, 40, etc., on graph $r = 4$. These y-values were constructed in red lines on $r = 4$. After the conversion of the H-values, which was done in the same way, a new graph was made.
The graph for $r = 4$ can also be used for other radii without preparing a new graph. Using graph 4 for an auger-hole of say $r = 6$, we have to multiply the H and y values as measured in the actual hole by 4/6. For instance: $r = 6$, $H = 60$ and $y = 30$: read on graph $r = 4$: H_{40} and y_{20}, etc.
It is often somewhat difficult to remember whether in this case we should multiply by 4/6 or by 6/4. It may therefore be helpful to remember that the radius of the graph used forms the numerator and the radius of the actual auger-hole the denominator.

In this formula k is expressed in m/24 hours. All other quantities are in cm or in sec.

k = hydraulic conductivity.

H = depth of hole below the groundwater table.

y = distance between groundwater level and the average level of the water in the hole for the time interval Δt.

r = radius of auger-hole.

S = depth of the impermeable layer below the bottom of the hole or the layer, which has a permeability of about one tenth or less of the permeability of the layers above.

Equation (2) represents an empirically derived approximate expression of the results of a number of relaxation constructions. Hence this formula does not show the exact relationship that should theoretically exist between the different quantities, although the value of k will be sufficiently accurate (maximum error: 20 %) if the following conditions are met:

$$r > 3 \text{ and } < 7 \text{ cm};$$
$$H > 20 \text{ and } < 200 \text{ cm};$$
$$y > 0.2\,H;$$
$$S > H;$$
$$\Delta y \leqslant 1/4\, y_o.$$

Equation (2) can also be written in another form, which facilitates calculations:

$$k = \frac{4000\, r^2}{(H + 20r)\left(2 - \frac{y}{H}\right) y} \frac{\Delta y}{\Delta t} \qquad (2a)$$

When *the impermeable layer is at the bottom of the hole* (S = 0) the following equation can be used:

$$k' = \frac{3600\, r^2}{(H + 10r)\left(2 - \frac{y}{H}\right) y} \frac{\Delta y}{\Delta t} \qquad (3)$$

5.3. EXAMPLES

Example No. 1 demonstrates the computation of the k-factor from the data obtained in the field based on fixed time intervals (Δt).

Example 2 demonstrates the computation of the K factor based on fixed intervals of the rise of the water level (Δy).

Example No. 3 illustrates some of the irregularities that may occur in the measurement data.

Example No. 4 shows that the k-factor computed will be too low if the measurements are continued for too long ($\Delta y > 1/4\ y_o$) or if too long a period elapses between bailing and starting the measurements.

EXAMPLE NO. 1 (FIG. 6)

Note: All readings are taken 40 cm above ground-level (see fig. 4 and fig. 6).

No.:			**Date:**	
Location:			**Technician:**	
D' = *240*	**D** = 200		**r** = *4*	**k estm.** = **m/day**
W' = *114*	**W** = 74		**S** = > *½H*	**k calc.** = 0.66 **m/day**
H = 126	**H** = 126			

t	**y_t'**	**Δy_t**
0	*145.2*	
10	*144.0*	1.2
20	*142.8*	1.2
30	*141.7*	1.1
40	*140.6*	1.1
50	*139.6*	1.1
Δy =	5.6	5.6

$$\mathbf{y_o} = \mathbf{y_o}' - \mathbf{W}' = 145.2 - 114 = 31.2$$
$$\mathbf{\Delta y} = \mathbf{y_o}' - \mathbf{y_n}' = \Sigma \mathbf{\Delta y_t} = 5.6$$
$$\mathbf{y} = \mathbf{y_o} - \tfrac{1}{2}\mathbf{\Delta y} = 31.2 - 2.8 = 28.4$$
$$\left.\begin{array}{l}\mathbf{H} = 126 \\ \mathbf{y} = 28.4\end{array}\right\} \mathbf{C} = 6.0 \text{ (read from Graph 1)}$$
$$\frac{\mathbf{\Delta y}}{\mathbf{\Delta t}} = \frac{5.6}{50} = 0.11$$
$$\mathbf{k} = \mathbf{C}\frac{\mathbf{\Delta y}}{\mathbf{\Delta t}} = 6.0 \times 0.11 = 0.66$$

Note: The text printed on the field-sheet is shown here in **bold** type; the field notes are in *italics*, and the work carried out in the office is designated by roman type.

After the readings have been taken it is desirable to have some check on the reliability of the measurements. The Δy_t of each measurement is, therefore, computed in order to see whether the consecutive readings are reasonable consistent. If the value of Δy_t decreases gradually, the readings may be averaged up to $\Delta y = 1/4\ y_o$ or, in this case, up to a Δy of 7 to 8 cm. Both conditions are met here, so that k can be computed.

EXAMPLE NO. 2.

If $\Delta y = 4$ cm and 5 readings have been taken ($4\ \Delta y$), then the difference between the first and the last Δt should preferably be no more than 20 percent. From the graphs it may be seen that a difference of 4 cm of the y-values results at the most 20% difference of the C.-value.

When the difference is much larger, e.g. the Δt-values being: 27-44-56-71, then large openings in the soil profile are occurring (cracks, holes caused by roots, wood or animals). In that case measuring should be repeated in an other place.

D' = *165*	**D** = 125	**r** = *4*	*K* **(estm.)** = (—) **m. / day**
W' = *100*	**W** = 60	**S** = $\geqslant \frac{1}{2}$ *H*	*K* **(calc.)** = 0,57 **m. / day**
H = 65	**H** = 65		

y_t	t	Δt
y_n[1]) = *124*	*84*	
		23
125	*61*	
		21
126	*40*	
		21
127	*19*	
		19
y_0' = *128*	*0*	

$$y = \bar{y}' - w' = 126 - 100 = 26, \quad H = 65 \Big\} \; C = 11{,}2$$

$$\frac{\Delta y}{\Delta t} = \frac{4}{84} = \frac{400}{84} \times 10^{-2} = 0{,}048$$

$$K = C \frac{\Delta y}{\Delta t} = 11{,}2 \times 0{,}048 = 0{,}54$$

t	y_t	Δy_t
0	31.5	
		– 1.5
10	*30.0*	
		– 1.2
20	28.8	
		– 1.1
30	27.7	
		– 1.2
40	26.5	
		– 0.9
50	25.6	
		– 1.1
60	*24.5*	

EXAMPLE NO. 3.

In this example we see that the first Δy_t is somewhat high. This is frequently the case, and is most probably caused by water dropping along the wall of the hole after the water has been bailed out.

Moreover, it is very easy to make a 1 mm error in reading the y_t. The rise of the measuring tape may also be somewhat irregular at times, since the steel tape or float may stick to the wall of the hole. But these errors are sufficiently eliminated by taking the average of 4–6 measurements. In the example given one would take for Δy: 30.0–24.5 = 5.5 and $y = y_o - \frac{1}{2}\Delta y = 30.0 - 2.8 = 27.2$.

For $\Delta t = 50$, $H = 80$, $r = 4$ and $S > H$:

$c = 9.0$ and $k = 9.0 \times 5.5/50 = 0.99$. (Graph 1)

EXAMPLE No 4.

t	y_t	Δy_t		
0	*30.3*			
15	28.8	− 1.5	$\Delta y/\Delta t = 5.8/60$	r = 4 (graph 1)
30	27.3	− 1.5	y = 27.4	S > ½H (graph 1)
45	25.9	− 1.4	C = 17.8	H = 35 (graph 1)
		− 1.4	k = *1.75*	
60	*24.5*			
75	23.2	− 1.3	$\Delta y/\Delta t = 4.9/60$	
90	21.9	− 1.3	y = 22.0	
105	20.7	− 1.2	C = 20.2	
		− 1.1	k = *1.65*	
120	*19.6*			
135	18.6	− 1.0	$\Delta y/\Delta t = 3.8/60$	
150	17.6	− 1.0	y = 17.7	
165	16.7	− 0.9	C = 23.2	
		− 0.9	k = *1.47*	
180	*15.8*			
195	15.0	− 0.8	$\Delta y/\Delta t = 2.9/60$	
210	14.2	− 0.8	y = 14.3	
225	13.5	− 0.7	C = 27.5	
240	12.7	− 0.7	k = *1.33*	

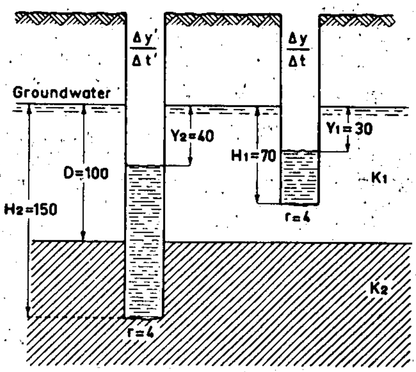
In order to demonstrate which errors are introduced if the measurements are continued for too long a time the k-factor has been computed for each group of five readings. Although $\Delta y/\Delta t$ should decrease, the product $C\frac{\Delta y}{\Delta t}$, and hence k, should be constant, but it can be seen that this is not the case here.

The decrease in the calculated k-factor is caused by the funnelshaped drawdown of the water-table around the hole and the corresponding decrease in the H-value. In example No. 4 all C-values have been calculated for H = 35 cm, but in this case the apparent H-values will have been H_{35}, H_{32}, H_{28} and H_{24}, respectively. If these H-values had been used, each of the four calculations would have given the same k-factor (k = 1.75).

6. AUGER-HOLES IN A LAYERED SOIL

If the profile consists of 2 layers having appreciable differences in hydraulic conductivity, the k-value of each layer can be determined if the water-table lies well in the upper layer. It will be necessary to work with two holes of different depth, and the bottom of the shallow hole should be at least 10–15 cm above the lower layer. In most cases the deep hole is made first in order to locate the boundary of the two layers (fig. 7).

Fig. 7.



If we call the hydraulic conductivity of the upper layer k_1 and the lower layer k_2, then the rate of rise in the deep hole is:

$$\frac{\Delta y'}{\Delta t'} = \frac{k_1}{C_o} + \frac{k_2}{C_2} - \frac{k_2}{C_o} \quad \text{or:} \quad k_2 = \frac{C_o \frac{\Delta y'}{\Delta t'} - k_1}{\frac{C_o}{C_2} - 1}$$

k_1 is computed from $\Delta y/\Delta t$ in the shallow hole and the C-value for H_1 and y_1, using graph $S > \frac{1}{2}H$.

$\frac{\Delta y'}{\Delta t'}$ is the rate of rise in the deep hole.

The C_2-value, corresponding with H_2 and y_2, can be read from the graph $S = 0$ or $S = > \frac{1}{2}H$, depending on the location of the impermeable layer.

The C_o-value is read from the graph $S = 0$, using D and y_2. The graph $S = 0$ is used in this case, because only horizontal flow has to be taken into account in the upper layer of the deep hole. This means, that for this purpose we may consider the lower layer being impervious.

EXAMPLE:

1) $\frac{\Delta y}{\Delta t} = 0.16$ $\quad \left.\begin{array}{l} H_1 = 70 \\ y_1 = 30 \\ S > \frac{1}{2}H \\ r = 4 \end{array}\right\}$ $C_1 = 9.4$. (graph 1) $\quad k_1 = 9.4 \times 0.16 = 1.5$

2) $\frac{\Delta y'}{\Delta t'} = 0.26$[1] $\left.\begin{array}{l} H_2 = 150 \\ y_2 = 40, \\ S > \frac{1}{2}H, \end{array}\right\} \begin{array}{l} C_2 = 3.9 \\ \text{(graph 1)} \end{array}$ $\left.\begin{array}{l} D = 100 \\ y_2 = 40 \\ S = 0 \end{array}\right\} \begin{array}{l} C_o = 6.3 \\ \text{(graph 2)} \end{array}$

$$k_2 = \frac{C_o \frac{\Delta y'}{\Delta t'} - k_1}{\frac{C_o}{C_2} - 1} = \frac{6.3 \times 0.26 - 1.5}{\frac{6.3}{3.9} - 1} = \frac{1.64 - 1.5}{1.62 - 1} = \frac{0.14}{0.62} = 0.22$$

7. POSSIBLE ERRORS AND VARIATIONS

The following possible errors have to be taken into account.

a. The maximum error in the graphs is estimated at 5 percent.

b. The error caused by a wrong measurement of H and y is inversely proportional to the magnitude of H and y.
For instance: a 1 cm error in the measurement of H causes a 2 percent error in the k-value if H = 50 and a 1 percent error if H = 100. The same is true of y. This shows that there is no need to measure H and y with an accuracy of millimetres.

c. If a wrong figure is used for the radius r the order of magnitude of the error is usually about 20 percent for half a centimetre difference in radius, or 20 percent for the difference of 1 cm between the diameter of the hole used for computing the k-factor and the actual diameter.

d. A difference of 10 percent is quite normal when the k-factor is measured several times in the same hole.

The *variation in k-factors* within short distances or between soil profiles classified as one soil type is often many tens of percents. On the other hand, there are thousandfold differences in the hydraulic conductivity of different soil types. Some soils have a very low hydraulic conductivity (k = 0.01), whereas others have a very high one (k = 10). Hence the order of magnitude is more important than an accurately „calculated" figure. After all, we are usually not interested in knowing the hydraulic conductivity of the soil in a plot 1 sq.m. in area, but rather in the hydraulic conductivity of a larger area. Consequently accuracy should be obtained rather by measuring the k-factor in many holes

[1]) If $k_1 = 1.5$ and $k_2 = 0$, the minimum rate of rise ($\Delta y'/\Delta t'$) in this case will be: 0.24 provided the upper layer is homogeneous within short distance (k_1 hole 1 = k_1 hole 2), according to the following calculation:

$\left.\begin{array}{l} H = 100, \\ y = 40, \\ S = 0, \end{array}\right\} C = 6.3,$ $\quad \frac{\Delta y}{\Delta t} = \frac{k}{C} = \frac{1.5}{6.3} = 0.24.$

all over the area, than bij measuring and calculating this factor with great accuracy in a particular hole.

The determination of hydraulic conductivity of the soil in a certain area should always be combined with a soil survey. There often is a close correlation between the soil characteristics as seen in the field and the k-factor of the soil, but this correlation can only be established on a regional basis.

RANGE OF HYDRAULIC CONDUCTIVITY VALUES IN THE NETHERLANDS IN m/day (HOOGHOUDT, 1952)

Sands: 0.1 for fine sands to 30 in coarse sands;

Clays: 0.01 to more than 30. Some clay soils have better permeability than coarse sandy soils;

Peats: 0.01 to more than 10. Phragmites peat is mostly very permeable; sphagnum and carex peat are often much less permeable.

Appendix I

TIME AVAILABLE FOR RELIABLE MEASUREMENTS ($\Delta y \leqslant 1/4\, y_o$), for k = 1 m/day and r = 4 cm .

y_o: in cm.	15	20	25	30	40	50	60	70	80	90	100	120	140
$\Delta y = 1/4\, y_o$:	3.75	5	6.25	7.5	10	12.5	15	17.5	20	22.5	25	30	35
	time in seconds												
H = 30:	109	117	131	146									
H = 50:		83	88	90	105								
H = 75:		60	63	66	72	78	87						
H = 100:		47	50	53	56	60	63	68	73	79			
H = 150:				37	39	41	43	46	48	50	52	57	63

Example of calculation: $\left.\begin{array}{l} H = 75 \\ y = 20 \end{array}\right\} C = 12.$

$$k = C\frac{\Delta y}{\Delta t}. \quad \text{For } k = 1: \qquad \Delta t = \Delta y \times C.$$

Δy or permissible range of measurement = 1/4 × 20 cm = 5 cm.

$\Delta t = \Delta y \times C = 5 \times 12$ seconds = 60 seconds.

For the case that H = 75 and y = 20 cm and k = lm/day, there are 60 seconds available for reliable measurements, or, if k = 0.1 m/day, the time available is 600 seconds = 10 minutes.

For a second bailing, the extra time involved is about 10 seconds.

It can be seen from the above that there is more time available for readings if H is small. Hence if the soil has a high permeability, H should be made as small as possible, and where the soil has a very low permeability it should be made as large as possible.

PERFORATED BRASS TUBE

In unstable sandy soils it is necessary to use a perforated tube. The auger is used up to the point where the hole becomes unstable. The perforated tube is then lowered into the hole. By moving up and down the bailer – which has a valve at the bottom – the mixture of sand and water enters the bailer and the tube can be pushed downwards.

Description of the perforated brass tube

2 mm thick, perforations about 4 mm apart and about 0.5 mm in diameter. The screen is cylindrical, 8 cm in outer diameter for a hole with a diameter of 8 cm, and 1 metre in length.

On both ends there is a reinforcement with a riveted ring.

For drawing the tube out of the borehole a kind of drawhook is useful. Cams for holding the drawhook are secured to the top of the screen tube.

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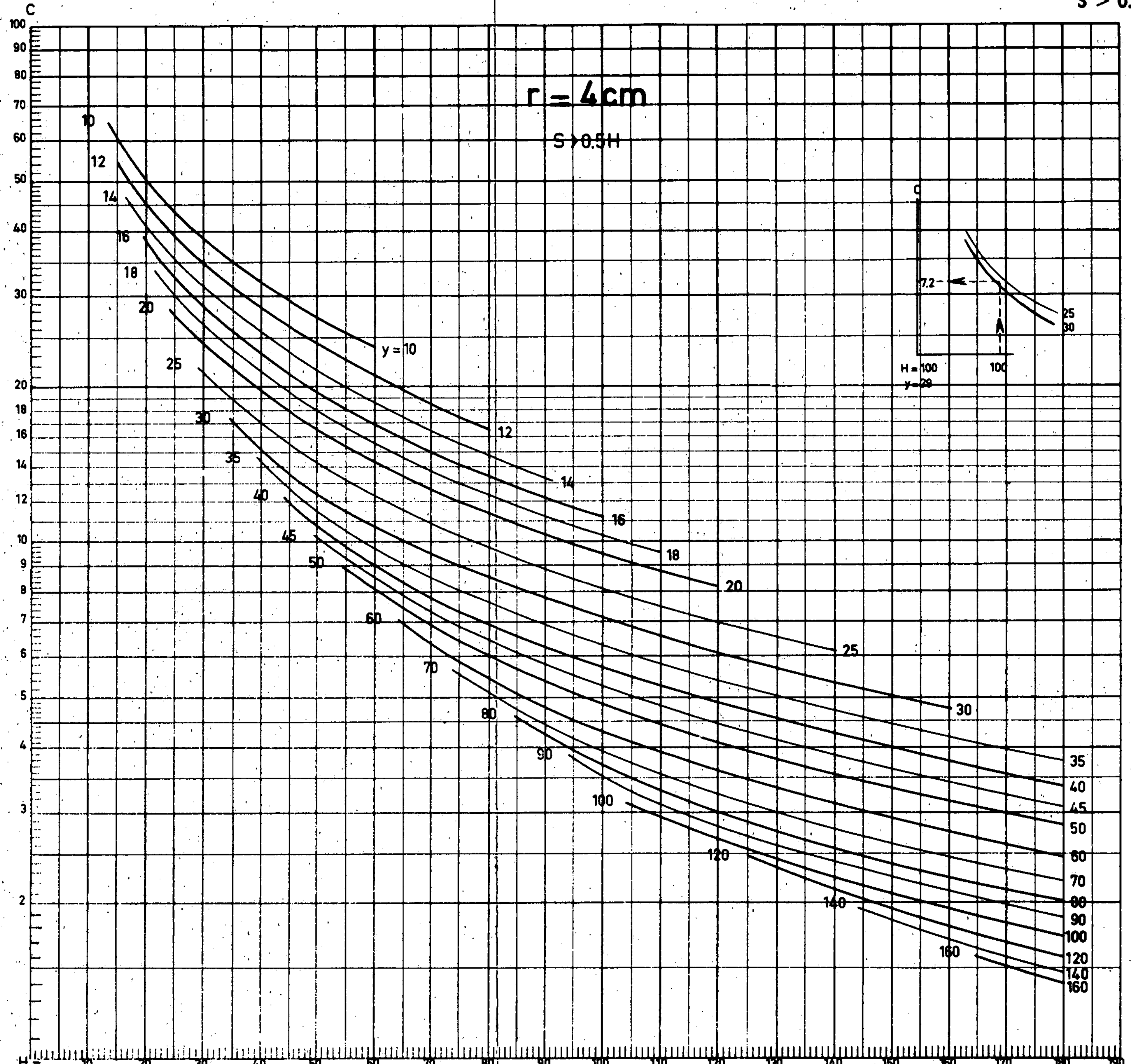
GRAPH 1

$r = 4$ cm

$S > 0.5\,H$



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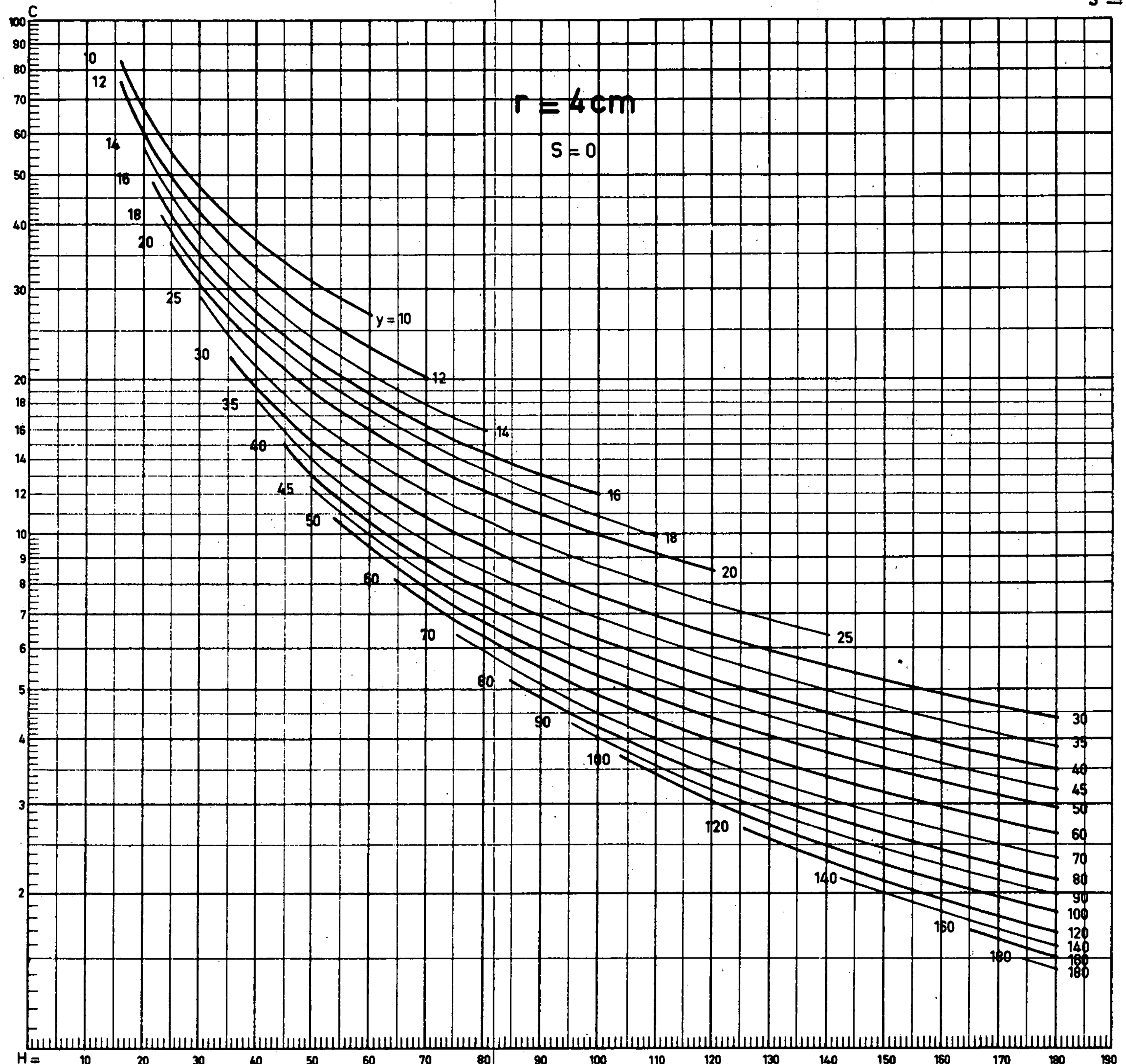
GRAPH 2

r = 4 cm

S = 0



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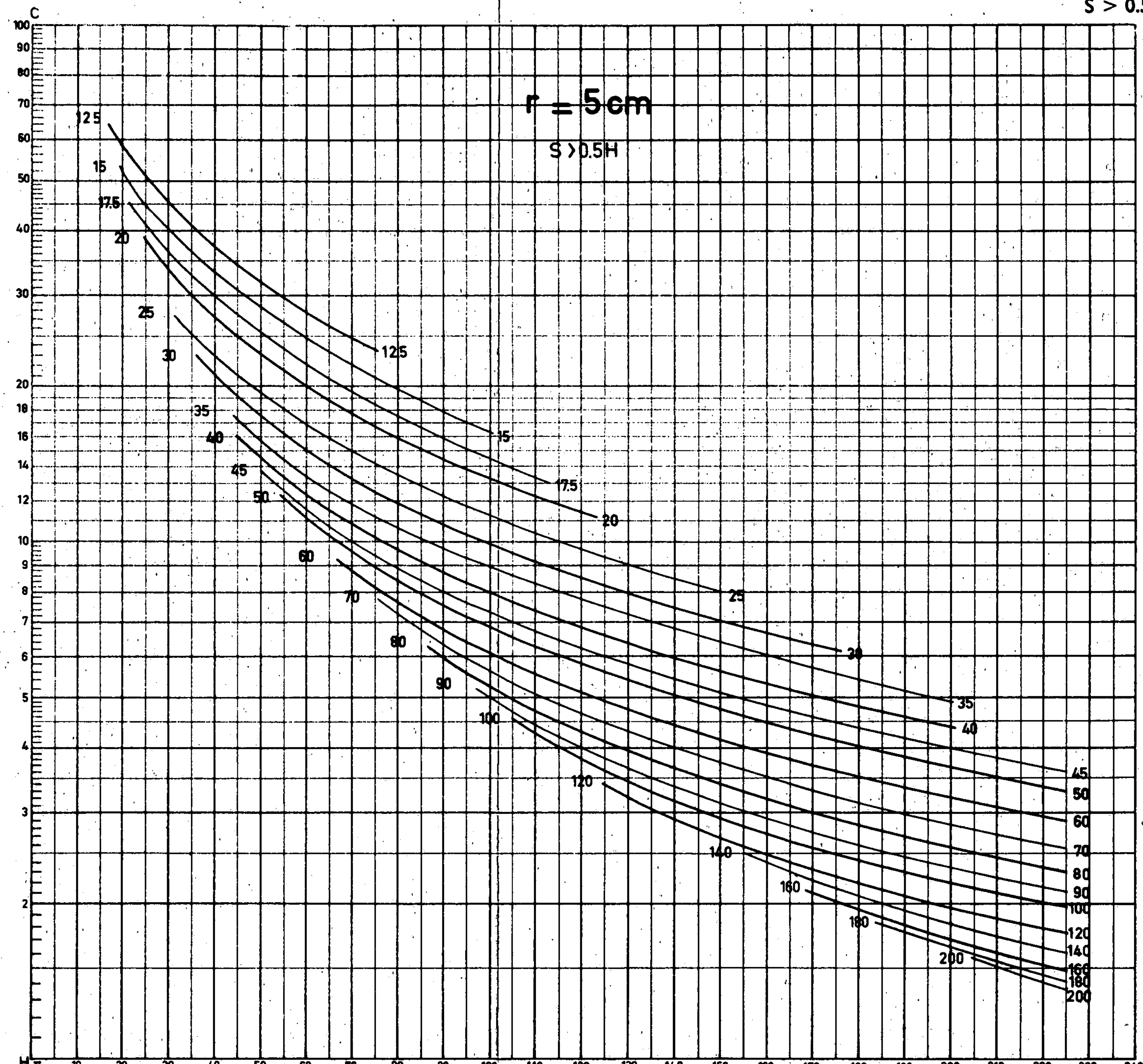
GRAPH 3

r = 5 cm

S > 0.5 H



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GRAPH 4

r = 5 cm

S = 0