

631.6 + 631.432 - 631.425.0015

SEPARA
No. 24085

SIBLIOTHEEK
INSTITUUT VOOR
BODEMVRUCHTSCULTUUR
GROENINGEN

CONCEPTION AND METHODS IN RELATION TO THE
DESCRIPTION OF SOIL STRUCTURES BY PHYS-
ICALLY SIGNIFICANT PARAMETERS

pm. Bijdrage J.C.V. en het Kew. van de
West-Europen Werkgroep van Bodemstructuur

28,
963 ?

Instituut voor Cultuurtechniek en Waterhuishouding
17, Prinses Marijkeweg - P.O. Box 35 - Wageningen -
The Netherlands. Telephone 3443

LIST OF CONTENTS

Conception and methods in relation to the description of soil
structure by physically significant parameters

	pag.
W.C. Visser : General approach of the description of soil structure in relation to land improvement practices and research	1
P.E. Rijtema : Capillary conductivity	14
K.E. Wit : Hydraulic conductivity	20
W.P. Stakman : Moisture-retention curves	24
Ph.Th. Stol : The equilibrium moisture content at various constant pF-values	35

CONCEPTION AND METHODS IN RELATION TO THE
DESCRIPTION OF SOIL STRUCTURE BY PHYS-
ICALLY SIGNIFICANT PARAMETERS

General approach of the description of soil structure in relation to land
improvement practices and research

The description of the soil structure should be based on reasonable physical conceptions and should be detached from instrumental- or methodological influences. Data, based on a conventional method may serve well in descriptive- and statistical studies, but are lacking as a basis for further theoretical development, as a basis for explanation of cause and effect and as a basis for transposing the results from one set of experimental conditions to another set of conditions.

Soil structure parameters will be valuable in studies of soil moisture behaviour, of aeration, of swelling and shrinking, of workability, of shearing resistance and of resistance against structure deterioration.

The physical phenomena of workability, penetrability by root growth, supporting power of the soil for the pressure of wheels or animal hoofs - to be grouped together as mechanical resistance - are not yet entirely understood. This limits the possibility of developing a sound physical picture of the soil structure.

The work at the Instituut voor Cultuurtechniek en Waterhuishouding (I.C.W.), Wageningen, aims at the development of the description of the soil structure in successive stages. The first aim is to give a normalized description of the pore size distribution, founded on a conception of distinguishing between adsorptive and structural influences. The next step is to develop a parameter for the relative level of structure by comparing the parameters for pore size distribution with the particle size distribution. This will show how the structure may vary in case of identical lithological properties.

The third step is to develop shape factors for the structural units of the pores. These shape factors, of importance for the conductivity of the soil, are known as the tortuosity factor and the ramification factor. The first gives the ratio between the point to point distance and the real distance covered by a water drop moving between these two points. The second parameter expresses the size distribution of the average diameter of the capillaries as flow channels of a certain length, as distinct from the pore size distribution where only the diameter over a zero length is object of description. The range covered by the pore-radii as found by the desorption curve differs from the range, found by analyzing fluid flow. The first range is larger, because the retention is influenced by all the radii, and the flow will react according to an average active radius which varies between narrower limits.

Shrinkage is studied as part of the description of the soil moisture depletion curve. The conception is based on the well-known soil mechanical fact that shrinkage is proportional to the log of the stress but, since shrinkage is to a greater part an irreversible process, the lowest limit from where the logarithmic proportionality is valid depends on the highest stress to which the sample was subjected in its history.

Up to the present no attention could be given to the analyses of properties of plastic flow and deformation as a basis for workability, root penetration, supporting power and further mechanical properties. Here, however, the basic parameters will follow from comparison of the soil moisture depletion curve with the curve for the shear resistance or viscous flow at varying moisture contents.

The central point in the conception of the determination of soil structure at the I.C.W. is, that structural characteristics determined as conventional single values restrict the possibility of further development of the theory and do not give sufficient insight into the basic relations.

The soils part of the structure problem has been simplified at the cost of increasing the difficulties to be surmounted in the biological, hydrological and mechanical part of the problem that will have to be solved with the aid of structure values.

The determination of soil structure becomes by using a curve fitting technique instead of laboratory determinations of empirical quantities, a calculation of parameters of formulae. The analyses to be used in the curve fitting technique are the routine determinations of soil particle distribution, desorption curve, the curve for capillary conductivity and the curve for viscous flow or shear. These parameters may be used if the pattern and quantity of flow for air or moisture, or the pattern of stresses have to be described for boundary conditions which differ from those prevailing in the soil sample during the routine analyses.

Description of the statistical structure characteristics

The retention of soil moisture serves as a means to determine the size distribution of the pore diameters. The soil moisture retention is, however, partly based on adsorption, partly on the probability distribution of the soil particles. It would be desirable to base the description of the retention curve on the log-normal probability distribution and the adsorption equation, which are given by:

$$P-v = P\alpha \int e^{-\beta^2(B-pF)^2} d(B-pF) \quad \frac{a}{\psi} = \left(\frac{v}{P}\right)^R$$

where:

P = pore space

v = soil moisture in volume percentage

ψ = moisture stress

pF = log ψ

α, β, a = constants

B = zero point log ψ scale

R = exponent of adsorption equation

e = base of natural log

d = differential sign.

The probability equation is however too complicated as a starting point for further theoretical development. A symplified formula is therefor used:

$$\frac{P-v}{P} = e^{-c(D-pF)} \quad \text{or} \quad \frac{P-v}{P} = e^{-1n\left(\frac{d}{\psi}\right)^c}$$

where:

c = activity constant

D = zero point of log ψ scale in symplified assumption

d = e^D .

The equations for the adsorption influence and the structure influence:

$$\frac{a}{\psi} = \left(\frac{v}{P}\right)^R \quad \text{and} \quad \frac{d}{\psi} = \left(\frac{P}{P-v}\right)^S$$

may be combined as assuming, that a percentual increase in ψ is the sum of the procentual influences on ψ of the adsorption factor and the structure factor.

The percentual increase is given by the first derivatives:

$$-a \frac{d\psi}{\psi} = RP \frac{dv}{v} \quad -d \frac{d\psi}{\psi} = +SP \frac{dv}{P-v}$$

The sum is:

$$-(a+d) \frac{d\psi}{\psi} = \left(\frac{RP}{v} + \frac{SP}{P-v}\right) dv$$

From this, the formula for the soil moisture depletion curve is derived.

The formula may be written as:

$$(A-pF) = C \log v - D \log(P-v)$$

$$\psi = a \frac{(P-v)^D}{v^C}$$

where:

A = combined zero point for pF-scale

C and D = activity factors

$\log a = A$.

Attention must be given to the fact that the formula describes moisture and air filled space - v and $(P-v)$ - in an identical manner and may serve for aeration problems as well as for moisture problems. The formula holds well if difficulties in assesement of P are overcome. If a saturated capillary zone exists - if therefor up to a certain value of ψ the soil remains

entirely saturated - then the pore space P of the formula is larger than the actual pore space P^* with an excess equal to ΔP .

If the soil shows swelling and shrinkage, then P is a function of $\log \psi$ from a certain value ψ^* upward. Therefore in that case ψ is equal to:

$$\psi = a \frac{(P - b(\log \psi - \log \psi^*) - v)^D}{v^C}$$

where:

b = shrinkage parameter.

The latter complication is of limited interest due to the magnitude of the normal experimental error of the moisture stress - moisture content determination. The excess ΔP is of considerable importance for moisture flow and is a valuable structure characteristic.

The value D is the second important structure parameter. C is more closely attached to the adsorptive properties. But the value of $1/(C+D)$ is of interest as a parameter for the range of the pore diameter distribution, in the same sense as the mean error is the parameter for the range of the probability distribution.

Determination of the geometrical structure parameter

The flow of air or water through soils is determined by the configuration of the flow path. The capillaries may be more or less tortuous in case of micro-stratification. The pore structure may be more or less intensily ramified. In a cubical arrangement of soil particles each pore has for one entrance five exits. In a tetrahedral arrangement there are only three exits. This number three or five is the constant of ramification.

This ramification governs the possibility that a number of voids are linked together by pores with a size larger or smaller than average. It determines the probability distribution of the active diameter of the capillaries which form a flow path between two distant points in the soil mass. The active size of the capillary tubes - active size taken as the size of a capillary tube of constant diameter with the same resistance as the real capillary of variable diameter - covers a narrower range than the diameter of capillaries, if assessed over units of zero length as the desorption curve does. The factor for the tortuosity of the flow path and the degree of ramification of the network of capillaries represent the geometrical parameters of soil structure.

From the desorption curve a function for the capillary permeability may be constructed in which the ramification factor must be chosen to comply with the results of the determination of the capillary conductivity at varying soil moisture stresses. A comparison of the function derived from the desorption curve with the observations of the capillary conductivity makes it possible to solve the structure parameters by a proces of curve fitting technique. In the series of conductivities at different soil moisture stresses the determination of the saturated conductivity is of crucial importance. In the integration of the conductivity distribution curve over the range of pore diameters, the largest size of pore existing follows only very inaccurate from the desorption curve due to the inaccuracy of the determination of total pore space. The problem of the largest size of the pores is in fact identical with the problem of determination of the height of the saturated capillary zone or the tension of air entry. Therefore

the integration does not take place between zero radius and a maximum radius, but the maximum radius is derived from the value of the saturated conductivity. The procedure may be explained by the following instance.

Given are the formulae for the desorption curve and its first derivative

$$\left(\frac{A}{\Psi}\right)^b = \frac{v^p}{(P-v)^{1-p}} \quad -b \frac{d\Psi}{\Psi} = \left(\frac{p}{v} + \frac{1-p}{P-v}\right) dv$$

Also are given the formulae for reducing the tension Ψ to the pore radius r and its first derivative, divided by Ψ :

$$r = \frac{2\tau}{g\rho} \frac{1}{\Psi} = \frac{a}{\Psi} \quad \frac{d\Psi}{\Psi} = - \frac{dr}{r}$$

where:

$$\begin{aligned} \tau &= \text{surface tension of fluid} & p &= \text{constant} \\ \rho &= \text{specific gravity of fluid} \\ \eta &= \text{viscosity of fluid} \\ g &= \text{gravity constant} \end{aligned}$$

The Poisseuille law for unit pressure head is:

$$\frac{dq}{dr} = \frac{dN}{dr} \frac{r^2}{8\eta} \tau r^2$$

Here dN/dr stands for the frequency with which a pore with radius r occurs. The frequency dN/dr follows from the increment in volume dv/dr as:

$$\frac{dN}{dr} = \frac{1}{\tau r^2} \frac{dv}{dr}$$

Assume a sample with $p = 1$. The first two formulae can be simplified to:

$$\left(\frac{A}{\Psi}\right)^b = v \quad -b \frac{d\Psi}{\Psi} = \frac{dv}{v} \quad v = - \frac{\Psi}{b} \frac{dv}{d\Psi} \quad \frac{dv}{d\Psi} = - \frac{b}{\Psi} \left(\frac{A}{\Psi}\right)^b$$

Change from Ψ and $d\Psi$ to r and dr

$$\frac{dv}{dr} = \frac{A^b b}{a} r^{b-1}$$

Insert in formula of Poisseuille and integrate:

$$\frac{dq}{dr} = \frac{1}{8\eta r^2} \frac{A^b b}{a} r^{b-1} \frac{1}{8\eta} r^4 = \frac{A^b b}{a} \frac{1}{8\eta} r^{1+b}$$

$$q = \frac{1}{8\eta} \frac{1}{a} \frac{A^b b}{(2+b)} r^{2+b} \quad \text{or} \quad q = \frac{1}{8\eta} a^2 \frac{A^b b}{(2+b)} \Psi^{1/(2+b)}$$

If the assumption is made that the tortuosity decreases exponentially with increasing value of r , than in the solution $(2+b)$ has to be replaced by $(2+b+d)$.

The integration takes place between $r = 0$ or $\Psi = \infty$ and the radius r_e or tension Ψ_e of the air entry point e , the tension therefore of the saturated capillary zone at its upper boundary. The integration for determination of the permeability for groundwater flow must therefore not be conducted till $\Psi = 0$; since between $\Psi = 0$ and $\Psi = \Psi_e$ all the pores are already filled and no new flow channels are added to the area of flow by a further decrease of Ψ .

By fitting the observations of a curve for unsaturated conductivity in the last formula, one will not find:

$$\frac{A^b b}{2+b} \quad \text{but} \quad \frac{A^b b^*}{2+b^*}$$

and not

$$\frac{a^2}{8\eta} \quad \text{but} \quad \frac{a^2}{8\eta} \frac{1}{\alpha}$$

The value of β in $b^* = \beta b$ accounts for the ramification factor, the value of α for the tortuosity factor. The values α and β may be solved by comparing the desorption curve with the capillary conductivity curve and - if for p the correct value is used, which changes the formula, for here the solution was given for $p = 1$ - they represent two soil structure parameters describing the relation to fluid flow.

Determination of the constants of the desorption curve

The solution of the constants of the desorption curve from observation data is simplest when performed graphically. The equation is therefore written as:

$$b(\log a - \log \Psi) = p \log v - (1-p) \log (P-v)$$

Now $\log v$ and $\log(P-v)$ are plotted against $\log \Psi$ in reverse directions, starting the v -scale at $\log v = 0$ and the $(P-v)$ -scale at $\log v = 2$. This gives two curved lines with vertical asymptotes at $\log v = 0$ and 2, and two inclined asymptotes, see fig. 1.

Draw a line between the two points of intersection of the $\log v$ - and the $\log(P-v)$ -curve. The angle with respect to the $\log \Psi$ -axis is equal to b . The two curved lines are intersected by a horizontal line at an arbitrary value of $\log \Psi$. The distance between the two points of intersection is equal to:

$$\log v - [2 - \log(P-v)]$$

This distance is split up in two parts by the oblique straight line. The lengths of these two parts are related to each other as p to $(1-p)$. Now the oblique straight line is described by:

$$[2 - \log(P-v)] + p \log v - [2 - \log(P-v)] = b(\log \Psi^* - \log \Psi)$$

or:

$$u + v = w$$

The distance u is found between the vertical axis and the $(P-v)$ -curve, the distance v is found between the $(P-v)$ and the v -curve. The length pv is the distance between the $(P-v)$ -curve and the oblique straight line. The distance w is measured along the vertical axis between the point of intersection with the oblique straight line and the arbitrary $\log \Psi$ -value.

The formula may be rewritten:

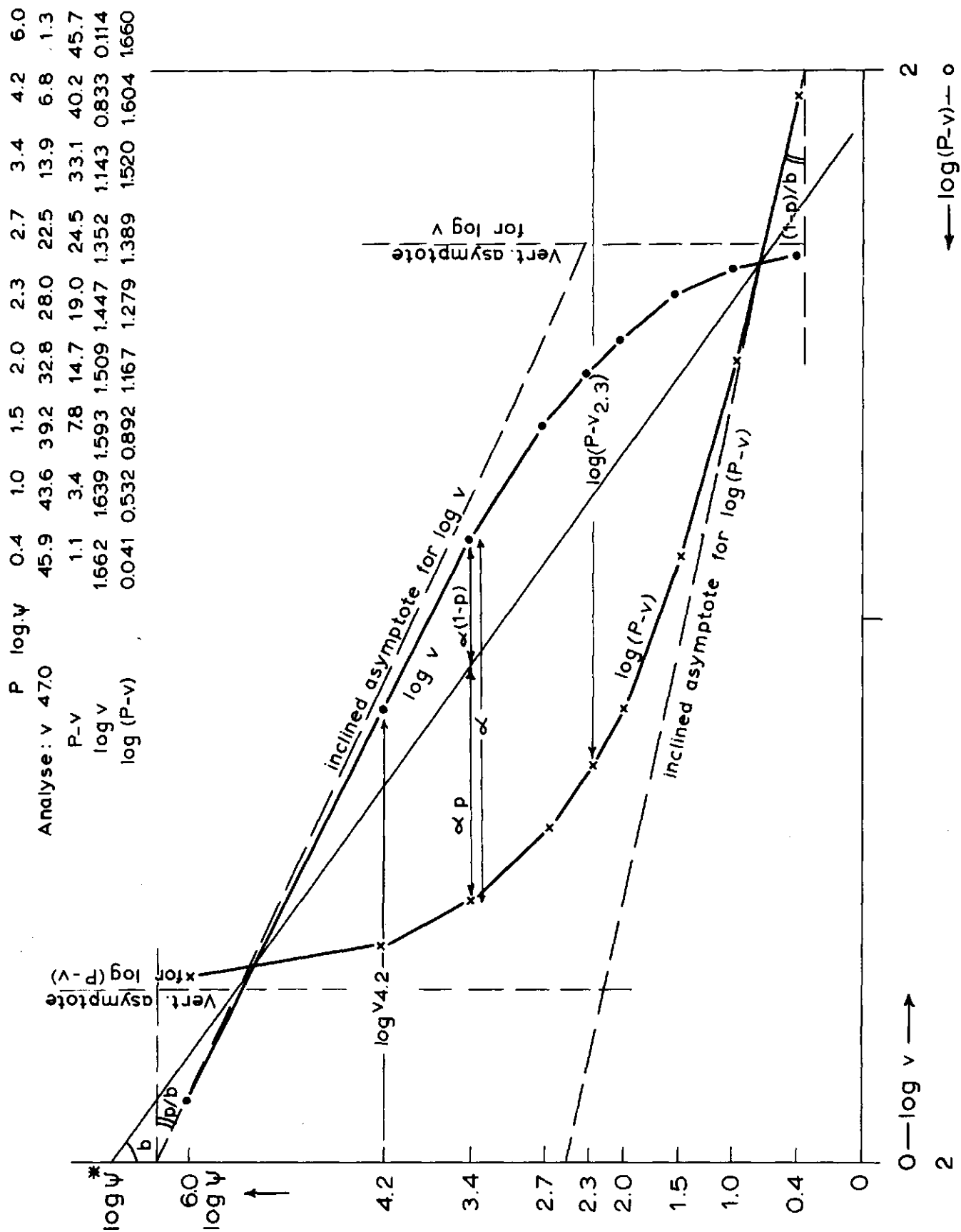
$$p \log v - (1-p) \log (P-v) = b \left[(\log \Psi^* - \frac{2(1-p)}{b} - \log \Psi) \right]$$

The value of b is found as the tangent of the oblique line with respect to the vertical axis. The value of p is found by plotting in a separate graph for each observation the distance between the $\log v$ - and $\log (P-v)$ -curve, against the distance between the $\log v$ -curve and the oblique straight line. The tangent of the line in this separate graph through the dots and the origin gives p .

Now the inclination of the slanting asymptote of the $\log v$ -curve is p/b , of the $\log (P-v)$ -curve is $(1-p)/b$. These angles are used to draw the curved lines more correctly at the lower values of $\log v$ and to check the estimated value of P for the $\log (P-v)$ -line. That value of P is used which gives the most accurate coincidence of the lower part of the $\log (P-v)$ -line and the asymptote with inclination $(1-p)/b$.

The value of a is found as $\log \Psi^*$ at the point of intersection of the vertical axis and the inclined straight line, reduced by the value of $2(1-p)/b$.

fig.1



Determination of the relative level of structure

The structure of a soil is not only to be considered as an absolute property, to be graded from good via medium to bad. It is also valuable to relate the structure parameter to the soil texture and to describe the soil structure for instance as: medium, but the best one may expect with a soil of such and such humus content, humus type, particle size distribution and structure forming factors - as lime status -, and so on.

The particle size distribution is a routine determination without difficulties. It is however a problem how to make a correct use in physics of this multi-value characteristic.

It was found that for the particle size integration curve the same formula is valid as for the moisture depletion curve. That the probability function holds for texture as well as pore space distribution is a matter of cause. The distribution of the particles and of the voids is clearly related to each other. For the volume occupied by the adsorbed part of the moisture it is not clear how the corresponding function with respect to the particle size has to be judged.

It is, however, a simple procedure to correlate the comparable parameters and determine the range of moisture depletion curves for the same soil texture or the mean depletion curve for a range of soil textures. In these correlations of identical parameters is ample scope for introducing independent soil structure characteristics as humus, lime status, or what might be of interest.

A regression analysis of the relation between the parameters of the size distribution for the particles, the voids and the further important factors describing the potentials of structure formation and structure destruction, is the object of empirical study in which the formulae with a simplified physical basis are forming the starting point.

W.C. Visser

Capillary conductivity

The determination of the capillary conductivity can be based on one of the two following principles.

1. Dynamic outflow measurements for which the equation of flow can be solved under certain conditions. If these conditions are not approached sufficient-ly, the lack of accuracy becomes considerable. Difficulties may arise too when the hydraulic conductivity of the underlying medium varies during the experiment.
2. Measurement of capillary conductivity with steady state conditions of flow has the disadvantage that a number of small tensiometers must be installed into the sample causing local disturbance in the soil column.

Both principles, however, offer possibilities to obtain information on the capillary conductivity of soils in relation to suction.

1. Determination of capillary conductivity from outflow data

For sampling and apparatus viz. moisture retention curves section A and B.

Theoretical considerations. In general the differential equations for the one-dimensional vertical flow is non-linear and difficult to solve analytically.

This equation, however, can be solved with the following suitable assumptions:

- a. By small increments of the suction a linear relationship exists between moisture content and suction, so $\theta(\psi) = A + B\psi$
- b. By these small suction-steps the capillary conductivity K may be considered as constant.
- c. The influence of gravity is neglected.

Under these conditions the equation for the outflow yields:

$$Q_t = Q_{\infty} - 2 Q_{\infty} \sum_{n=1}^{\infty} \frac{h^2 l^2}{\alpha_n^2 [h l (h l + 1) + \alpha_n^2]} e^{-D \alpha_n^2 t / l^2}$$

where:

Q_t = outflow after time $t = t$ (cm^3)

Q_{∞} = outflow after time $t = \infty$ (cm^3)

$hl = \alpha \tan \alpha = \frac{Kpl}{l_p K}$

l = length of the sample (cm)

K = capillary conductivity of the soil (cm/day)

l_p = thickness of the underlying medium (cm)

K_p = hydraulic conductivity of the medium (cm/day)

D = diffusivity = K/B where B equals the slope of the moisture-retention curve.

This infinite series converges very rapidly and for values of $t > 0.3 l^2 / \alpha_1^2 D$ the second term is already less than 1% of the first one. For the calculation of the capillary conductivity the higher terms are neglected and the e-functions nomogramme can be used (viz. pag 35).

Calculation procedure. Plot the outflow data against time and select a curve of the monogramme which will fit in with the experimentally obtained points. Determine the maximum loss of water (Q_{∞}), the interception point ($Q_{t(0)}$) of the fitting curve with the outflow-axis, the translation of the y-axis of the nomogramme in regard to the outflow-axis and the factor b of the fitting curve. From the translation of the y-axis of the nomogramme the value $Q_{\infty} - Q_{t(0)}$ can be easily calculated. This renders it possible to calculate the value

$\frac{Q_{\infty} - Q_{t(0)}}{Q_{\infty}}$ both from the interception point of the fitting curve and from

the translation of the y-axis. Either method must produce the same value. This value is only dependent on hl and α_1^2 . Values of $Q_{\infty} - Q_{t(0)}$ with the corresponding values of hl and α_1^2 are given in table 1.

Table 1. Values of $\frac{Q_{\infty} - Q_t(0)}{Q_{\infty}}$ with corresponding values of hl and α_1^2

$\frac{Q - Q_t(0)}{Q}$	hl	α_1^2	$\frac{Q - Q_t(0)}{Q}$	hl	α_1^2
0.9995	0.1	0.0968	0.8740	10	2.04
0.9988	0.2	0.188	0.8462	20	2.24
0.9954	0.5	0.426	0.8351	30	2.31
0.9862	1.0	0.740	0.8296	40	2.35
0.9633	2.0	1.158	0.8260	50	2.37
0.9432	3.0	1.425	0.8232	60	2.39
0.9263	4.0	1.60	0.8215	70	2.40
0.9143	5.0	1.72	0.8203	80	2.41
0.9024	6.0	1.82	0.8190	90	2.41
0.8935	7.0	1.89	0.8182	100	2.42
0.8858	8.0	1.95	0.811	∞	2.465

From the given outflow functions follows that:

$$D = \frac{b l^2}{2 \alpha_1^2}$$

where:

b = the factor of the curve fitting through the experimentally obtained points

α_1^2 = factor determined from the value $\frac{Q_{\infty} - Q_t(0)}{Q_{\infty}}$

l = length of the sample.

The slope B of the moisture-retention curve depends on the maximum outflow (Q_{∞}), the volume (V) of the sample and the increment ($\Delta \Psi$) of the suction. This relationship is given as follows:

$$B = \frac{Q_{\infty}}{V \Delta \Psi}$$

From the calculated values D and B the capillary conductivity can be determined applying the relation:

$$K = DB$$

2. Determination of capillary conductivity under conditions of steady state flow

a. Infiltration method. Undisturbed soil samples are taken in plastic cylinders (diameter 8 cm, length 15 cm). Into each cylinder 3 small tensiometers are installed at intervals of 5 cm. By the application of large infiltration rates the sample is placed upon a cylinder of equal diameter filled with coarse sand. The cylinder has a free outlet. On top of the sample another cylinder filled with coarse sand is placed. In order to ensure good distribution of the infiltration water over the whole surface area, the water is flowing through some layers of filterpaper into the coarse sand. The constant infiltration rate is realized by means of a calibrated perspex cylinder of constant diameter filled with water, lifted very slowly by a small motor driven winch at constant speed. The cylinder is connected with an over-flow system, that conducts the infiltration water to the top cylinder (viz. fig.2).

Steady state conditions have been reached when the discharge equals the infiltration rate. The suction at the various heights in the sample is read from the tensiometers. The capillary conductivity can be calculated from the relation:

$$K = \frac{V}{-\frac{\Delta \Psi}{\Delta h} + 1}$$

where:

K = capillary conductivity (cm/day)

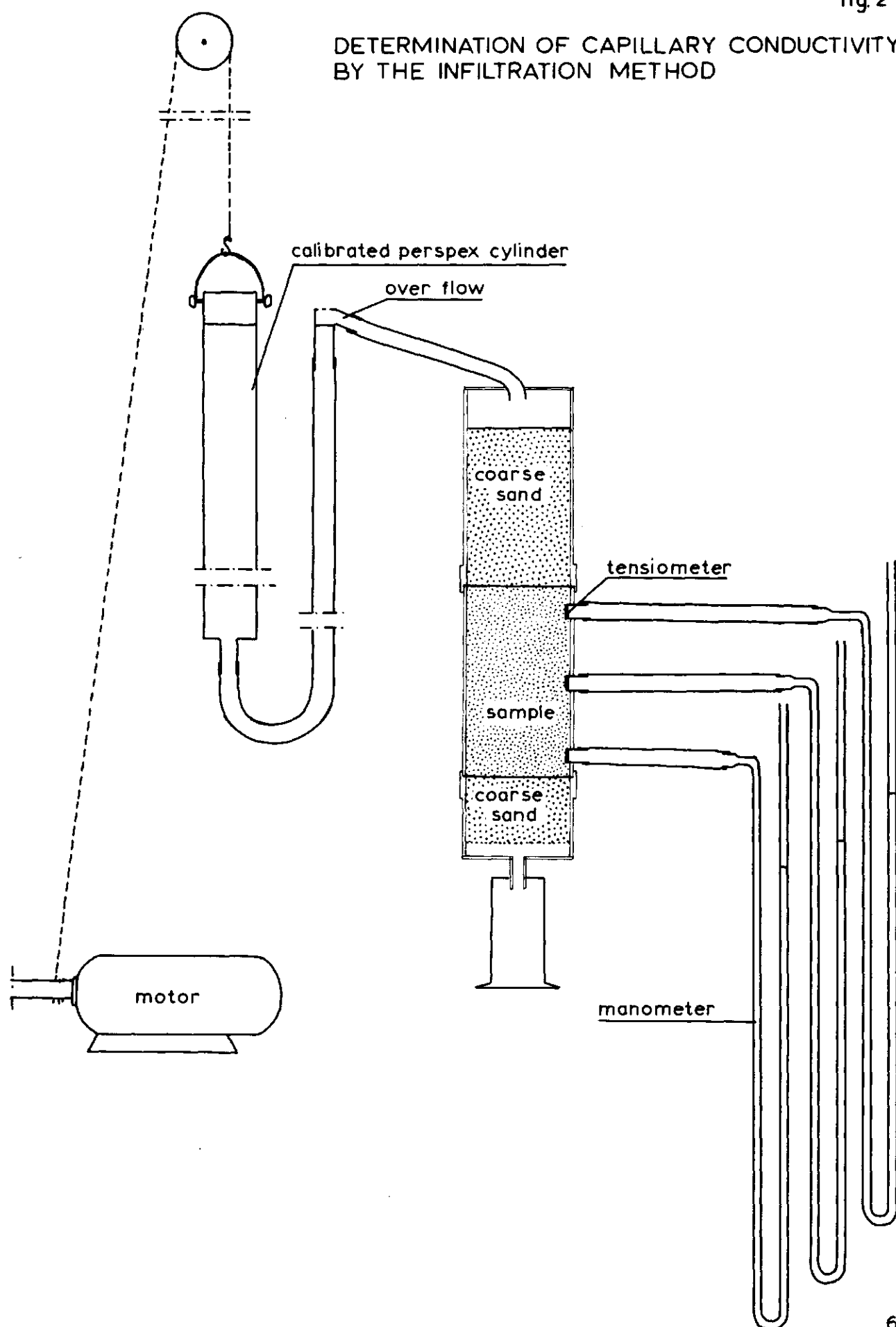
V = infiltration rate (cm/day)

$\Delta \Psi$ = difference in suction between upper and lower tensiometer (cm water)

Δh = distance between the tensiometers (cm).

fig. 2

DETERMINATION OF CAPILLARY CONDUCTIVITY BY THE INFILTRATION METHOD



62 c
106-1

By varying the diameter of the perspex cylinder or changing the speed of the winch a series of infiltration rates can be obtained. With small infiltration rates the lower cylinder with coarse sand can be exchanged for one filled with very fine sand to which a suction can be applied in order to effect large gradients enabling the determination of the capillary conductivity for a large range of suctions. In this case the discharge has to pass an over-flow system, which regulates the suction.

Evaporation method. Undisturbed samples are taken with plastic cylinders (diameter 8 cm, length 15 cm). Into each cylinder 3 small tensiometers are installed at intervals of 5 cm. The sample is placed upon a cylinder with the same surface area. This cylinder is filled with very fine sand, that remains saturated until a suction of 200 cm. The sand is in communication with the level of free water, kept constant by means of a calibrated mariotte system.

In order to realize constant evaporation the top of the sample is connected with a small box through which dry heated air is blown at a constant velocity (viz. fig. 3).

Daily readings from the tensiometer and observations of the loss of water from the mariotte system are recorded until equilibrium has been attained. At steady state conditions the capillary conductivity can be calculated from the relation:

$$K = \frac{V}{\frac{\Delta \Psi}{\Delta h} - 1}$$

where:

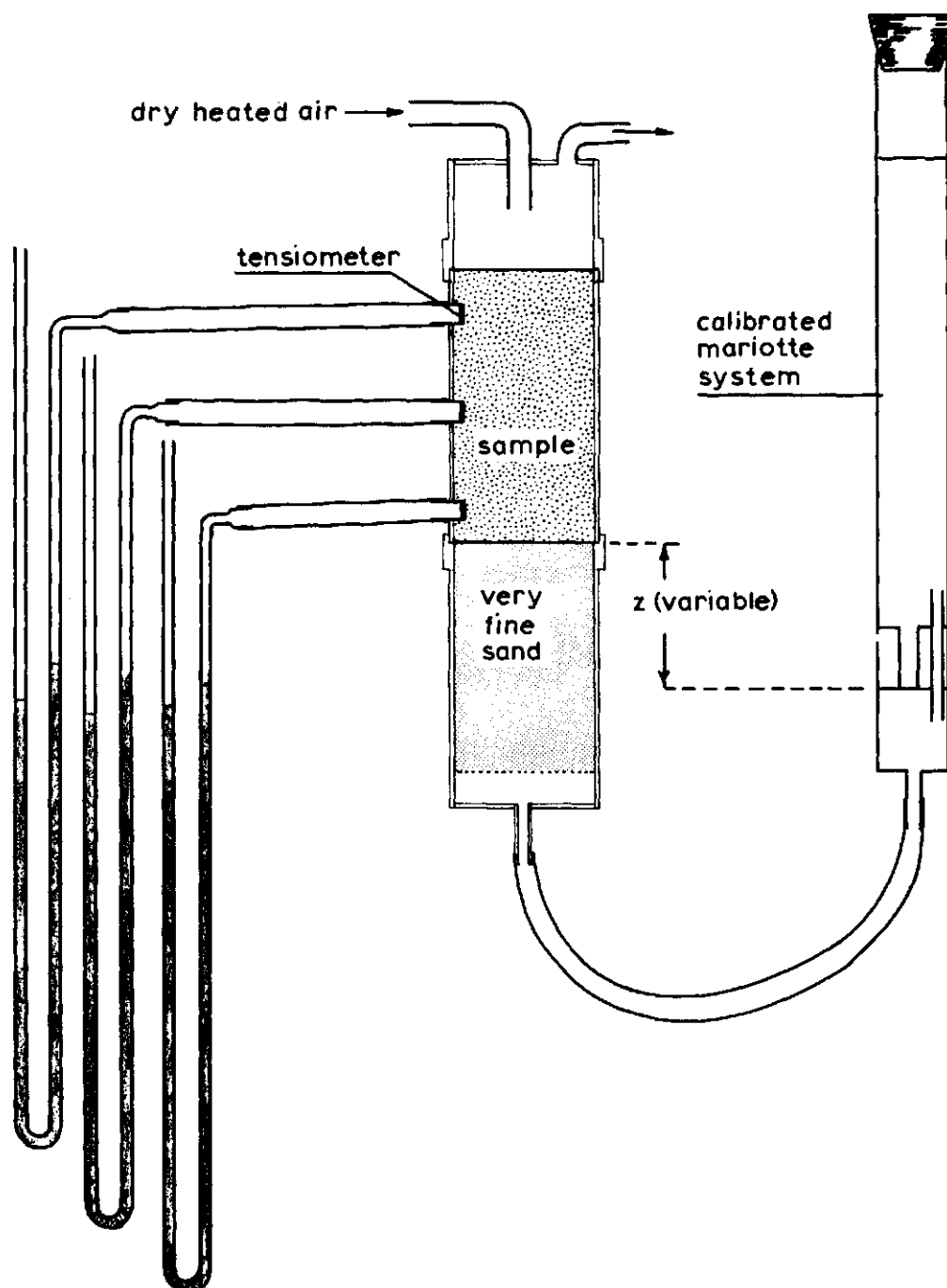
K = capillary conductivity (cm/day)

V = evaporation rate, read from the mariotte system (cm/day)

$\Delta \Psi$ = difference in suction between upper and lower tensiometer (cm/water)

Δh = distance between the two tensiometers (cm)

The suction in the soil sample can be varied over a large range by means of vertical adjustment of the mariotte system.

DETERMINATION OF CAPILLARY CONDUCTIVITY BY THE
EVAPORATION METHOD

References

- Rijtema, P.E. 1959. Calculation of capillary conductivity from pressure plate outflow data with non-negligible membrane impedance. Technical Bulletin 12 of the Instituut voor Cultuurtechniek en Waterhuishouding
- _____ 1959. De formule voor het vochtverlies van een pF-monster. Stencil of the Instituut voor Cultuurtechniek en Waterhuishouding
- Stol, Ph.Th. An e-function nomogramme as aid to the determination of the equilibrium moisture content and the capillary conductivity of soil samples (in press)

P.E. Rijtema

Hydraulic conductivity

Data both on horizontal and vertical hydraulic conductivity can be obtained from laboratory tests. Thus the presence of semi-permeable layers, impeding the flow of water, can be verified.

The inter-relation between hydraulic conductivity and soil physical properties such as granular composition, soil moisture retention, porosity and micro-structure can be traced. Also laboratory results can be compared with those obtained from field-tests (auger hole method and pumping tests).

Sampling and preparation of the cores

For undisturbed soil samples, either taken in horizontal or vertical direction up to a depth of 1 to 2 meters stainless steel cylinders (diameter 5 cm, height 5.1 cm) are used.

For sampling complete and undisturbed cores below the groundwater table up to a depth of 50 meters an apparatus has been designed that can be used in all kinds of layers, with the exception of coarse gravel. This apparatus is operated on the principle that the sampling tube is closed hermetically at the top after being inserted into the soil.

With fine sandy-, clay- and peat soils the capillary forces between the soil particles warrant the sample remaining intact when being raised. However in the case of coarse sandy soils it is also essential to support the soil column at the bottom. Both closing at top and support at bottom are effected with inflatable rubber tubes.

The zinc tubes fitting this apparatus have a diameter of 6.2 cm and a length of 30 cm. Prior to transport both ends of the sample thus obtained are sealed with a mixture of paraffine and vaseline.

The conductivity apparatus consists of a water-filled container (length x width x height = 130 x 35 x 40 cm) having a capacity of 50 samples. The level inside is kept constant with an overflow.

The samples taken above the groundwater table are saturated first. After this they are attached with screwcaps to collecting cylinders and fixed inside the container.

The zinc tubes are directly suitable for the tests after removal of the sealing mixture. The top of the collecting cylinders or zinc tubes extends above the water level, whereas the water inside, covering the top of the sample, remains below this level. The hydraulic head thus obtained will cause the water to flow through the sample from bottom to top. Dependent on the granular composition of the samples the hydraulic head is varied between 2 and 20 mm, to be measured with a sliding gauge accurate to 0.1 mm.

To prevent a reduction in the hydraulic conductivity, due to accumulation of bacteria near the inlet of the sample, 0.1% phenol is added to the de-ionisized water used for the tests.

Procedure

The calculation of the hydraulic conductivity necessitates the following laboratory measurements: rate of percolation, diameter of the samples, hydraulic head and temperature of the water. When the rate of flow is very small the evaporation of the water inside the collecting cylinder or tube, must be taken into account.

Dependent on the rate of flow of the water through the sample two methods can be employed:

- 1) constant-head method
- 2) falling-head method.

The constant-head method is used to measure factors affecting the hydraulic conductivity of sandy soils. The volume of water, percolating through the sample in a given time, is measured in a burette.

The samples in zinc tubes, are taken in vertical direction only. For the calculation of the transmissivity factor (i.e. the product of

the layer thickness and the average horizontal conductivity) data on the horizontal hydraulic conductivity must be obtained.

For this purpose two tubular filters are mounted vertically in the sample, after which both ends of the zinc tube are sealed.

As the tubular filters are in communication with the water levels resp. out- and inside the zinc tube, the hydraulic head will effect a horizontal movement inside the sample. The water displaced is measured in a burette.

The falling-head method is used to measure factors affecting the hydraulic conductivity of clay and peat soils. The rising of the water level inside the collecting cylinders or zinc tubes is also measured with a sliding gauge.

For soils with an extremely small hydraulic conductivity, an apparatus was designed, enabling the application of large hydraulic heads.

Calculations

The rate of flow through the sample may be expressed by the following equation:

$$Q = kiF,$$

where:

Q = the volume of water passing through the sample (cm^3/day)

i = the hydraulic gradient

F = the cross section of the sample (cm^2)

k = the permeability factor (cm/day).

With the falling-head method:

$$dQ = -\frac{dh}{dt} F' = k \frac{h}{L} F$$

Integrating between the limits, $h = h_1$, $h = h_2$ and $t = t_1$, $t = t_2$ gives:

$$\int_{h_1}^{h_2} \frac{dh}{h} = - \frac{kF}{F'L} \int_{t_1}^{t_2} dt$$

$$k = 24 \frac{F'L}{F(t_2-t_1)} \ln \frac{h_1}{h_2}$$

where:

F' = the diameter of the collecting cylinder (cm^2)

L = the length of the sample (cm)

F = the cross section of the sample (cm^2)

h = the hydraulic head (mm)

(t_2-t_1) = the time interval expressed in hours.

For the zinc tubes $F'/F = 1$, further corrections are made for the temperature and the evaporation.

References

- Gupta, R.P. and D. Schwarzendruber. 1962. Flow-associated reduction in the hydraulic conductivity of quartz sand. Proc. Soil Sc. Soc. Am. 26-1, 6-10
- Wit, K.E. 1960. Meting van de doorlatendheid in ongeroerde monsters. Interne mededeling of the Instituut voor Cultuurtechniek en Waterhuishouding
- _____ 1962. An apparatus for coring undisturbed samples in deep bore-holes. Soil Science, August '62, vol. 94-2
- _____ Apparatuur voor het meten van de doorlatendheid in ongestoorde monsters (in press)

K.E. Wit

Moisture-retention curves

A. Sampling and preparation of soil cores

Apparatus. Stainless steel cylinders (inside diameter 50 mm, height 51 mm, contents 100 cm³), holder for cylinders (to which attached grip, or hydraulic jack or auger), spade, garden shovel, knife, wooden sample boxes (for 18-24 cylinders) lined with rubber sheets inside, plastic bags, balance.

Procedure. Dig a pit and take either horizontal or vertical undisturbed soil samples in duplicate at the required depth; for that purpose press the retainer cylinders with the cutting edge into the soil, using the cylinder holder with grip or (for dry heavy clay soils) the hydraulic jack. Instead of digging a pit, an auger for volumetric cores can be used. Dig out the cylinders, roughly trim the cores with a knife and transport to the laboratory in the wooden boxes, which have been designed to reduce moisture losses to a minimum and to protect the cores from being disturbed. Collect disturbed soil from the same spot in a plastic bag for the higher pF-values. Trim the cores with a knife to obtain a flat surface at both ends of the cylinder and weigh correct to 0.1 gram (= initial weight).

Smearing and clogging of the surfaces of wet clay cores cannot altogether be avoided; in that case roughen the surfaces with a small hacksaw blade. Attach a hydrophil nylon cloth with a rubber band to cover one of the surfaces of the core.

B. Determination 0-1 atmosphere percentages

Apparatus. Sandbox with drainage system, balance, drying oven. The sandbox apparatus consists of a stainless sheet steel box, gauge 1.25 mm, length x width x height = 600 x 300 x 350 mm, filled with fine sand (so called 'Blokzijkl'-sand, containing approx. 77% of the fraction 37-50 μ and 12% of the fraction 50-75 μ , the air entry value is approx. 150 cm of water). The surface of the sand is covered with a nylon cloth. The drain inside the sandbox near the bottom consists of a frame of P.V.C.-conduit pipes with

slotted underside and wrapped in hydrophil nylon cloth. The outlet is in communication with a levelling bottle, adjustable along a graduated brass stand by means of which a tension of more than 100 cm of water (pF 2.0) can be realized, as taken from half-way the cylinders.

For higher tensions a sandbox apparatus is used with a supplementary layer of kaolinite applied on top of the sand surface. The air entry value of the kaolinite is considerably higher than 500 cm of water (pF 2.7).

Procedure. Adjust the levelling bottle in such a way that the water surface inside is level with the surface of the sand. Place the samples inside the sandbox with the nylon cloth on the nylon tissue of the sand surface. Arrange the passage of water from the supply bottle into the sandbox until the water is 1 cm below the top of the cylinders. Place lid on the sandbox and let samples saturate in 1 to 3 days, depending on soil type and initial moisture content. Readjust the water level to the surface of the sand, thus obtaining a tension of $2\frac{1}{2}$ cm of water (pF 0.4). Let the samples stand overnight, wipe the excess water from the cylinders and weigh correct to 0.1 gram.

Replace the cylinders in the sandbox with the levelling bottle adjusted at 10 cm below half the height of the cylinders. Let the samples stand for approx. 3-7 days, depending on soil type, and weigh (pF 1.0). Follow the same procedure at tensions of 31.6 and 100 cm of water (pF 1.5 and 2.0). For very heavy clay or peaty soils more time may be required to attain equilibrium.

With the kaolinite sandbox tensions of 200 and 500 cm of water (pF 2.3, resp. 2.7) are realized. The equilibrium content is reached after 6-14 days. Expose the samples to 105°C in the laboratory oven for 24 hours and weigh.

To control the equilibrium moisture values, use can be made of an e-function nomogram (see separate description); for this purpose weighings must be carried out at certain intervals.

Calculations. Subtract the gross oven-dry weight of each sample from the gross 'initial weight' resp. the gross equilibrium values at each tension.

The figures obtained give volume percentages of moisture.

Apparent specific gravity (bulk density) is calculated by subtracting the weight of the steel cylinder from the gross oven-dry weight and by dividing the obtained result by 100.

C. Determination 2.6 and 15 atm. percentages (pF 3.4 and pF 4.2)

Apparatus. Three pressure membrane units with cellophane PT 600 membrane and nylon gauze, plastic (Vinidur) soil-retaining rings 1 cm high and 3.3 cm diameter, precision balance (Mettler K 7), laboratory oven, moisture boxes, steel cylinder with compressed air, reducing valve, 20 atm.-manometer, sub-division 0.2 atm., 50 cm³ burette.

Procedure. Transfer some 100 grams of the sample into a beaker of 150 cm³ without disturbing the natural crumbling. Add water carefully until the soil is nearly saturated; small clods of clay should be submerged for their greater part. Samples with an initial moisture content of about field capacity are sufficiently saturated in 1 or 2 days. In the case of air dry samples it depends on soil type if, and how long, saturation will have to be prolonged. The saturation period may vary between 2 days for light sandy soils and 6 days for heavy clay soils.

Especially in the case of the 2.6 atm.-determination (pF 3.4) the structure of the soil must not be disturbed; for the determination of the 15 atm.-percentage this does not matter as at wilting point structure has no influence anymore.

Arrange the numbered Vinidur rings in the pressure membrane apparatus on two layers of cellophane PT 600 membrane. The membranes have beforehand been immersed in water during a period between 3 and 24 hours.

Fill the rings with the moistened soil from the beaker, using a spatula. With heavy clays, cut a piece of a clod the size of the ring contents. The spatula is used to 'vibrate' the soil into the ring to prevent air entrapment and to let the soil achieve good contact with the membrane. Place a small container with water drenched cotton-wool in the pressure chamber to realize a high relative humidity. For the 15 atm.-determination the cotton-

wool may be drenched in a saturated solution of barium nitrate or ammonium oxalate (relative humidity appr. 98.85% = pF 4.2). Close the pressure membrane apparatus and admit air into the pressure chamber at a pressure of 2.6 resp. 15 atmospheres.

The outflow of water is collected in a burette. Once the water level inside the burette remains constant, equilibrium value has been reached, which will take for:

light sandy soils	:	approx. 3 - 5 days
sand and sandy loam soils	:	,, 4 - 7 ,,
silty and clay soils	:	,, 6 - 8 ,,
basin clay soils and peaty soils:	:	,, 8 - 12 ,,

Next, release the pressure, open the press, transfer the samples quickly into the moisture boxes, weigh (correct to 0.1 gram), dry in the oven for 16 hours at 105°C and weigh again.

Remarks. The determination of the 2.6 and 15 atm.-percentages is carried out in triplicate; the soil sample is distributed over the three pressure membrane units. A standard sample of known water retention properties is to be included in each unit. If the moisture content of one standard sample deviates from the standard value by more than $\pm 5\%$, the moisture content of the other samples in the pressure membrane unit concerned will have to be determined again.

Calculations. Calculate from the loss of weight the moisture percentage (grams moisture per 100 grams of oven-dry soil) and average the moisture contents of the three identical samples. Convert this mean percentage of weight into volume percentage with the aid of the apparent specific gravity (i.e. the weight of 1 cm³ oven-dry soil), that is known from the determination of the lower pF-values with cylinders of 100 cm³ content:

volume % of moisture = weight % of moisture x

$\frac{\text{x oven-dry weight of 100 cc volumetric sample}}{100}$

D. Determination pF 6.0 (approx.) at atmospheric conditions

Apparatus. Hygrograph, psychrometer, thermometer, vaporizer, Petri-dishes (diameter 80-100 mm) or ceramic crucibles (diameter 40 mm), balance, drying oven, desiccator with silicagel.

Procedure. The determination should be conducted inside a room with minute temperature- and relative humidity fluctuations.

Spread a layer of soil of approx. 0.5 cm thickness evenly into two Petri-dishes (duplicate determination, about 25 grams of soil at field moisture content in each dish). Vaporize water over the sample; it is not necessary to saturate the samples, a moisture content of about field capacity is sufficient. In case of difficulties when moistening fairly dry samples, the soil is stirred gently with a spatula after application of some water.

Weigh correct to 0.01 gram after a few hours and repeat weighings every day. Determine at the same time the relative humidity from the dry and wet bulb readings of the psychrometer. A hygrograph is used to register the relative humidity over the period concerned.

Once constant weight has been obtained (after 2-5 days), the samples are exposed to 105°C in the laboratory oven for 16 hours and after that allowed to cool in a desiccator with silicagel. Weigh quickly as soon as the Petri-dishes have cooled down sufficiently to allow handling, taking care to replace the lid on the desiccator.

Remarks. For sandy soils use ceramic crucibles containing approx. 2 grams of the sample. After reaching moisture equilibrium, weigh on an analytical balance (for example Mettler B 5) correct to 0.1 mg. Follow the drying- and weighing procedure mentioned above. Weigh quickly.

Calculations. For the determination of the weight percentage of moisture and conversion into vol.% of moisture viz: Section C - Calculations.

The following equation gives the correlation between relative humidity and moisture tension:

$$h = \frac{R\theta}{Mg} e^{\log \frac{H}{100}}$$

where:

h = suction in cm of water

H = relative humidity

R = universal gas constant (8.315×10^7 ergs.mole⁻¹ °C⁻¹)

M = molecular weight of water (18.0 gm mole⁻¹)

θ = absolute temperature (°Kelvin)

g = acceleration of gravity

$$pF = {}^{10}\log h = {}^{10}\log \left(2.303 \frac{R\theta}{Mg} \right) + {}^{10}\log (2 - {}^{10}\log H)$$

For 15°C this equation becomes: $pF = 6.4946 + {}^{10}\log (2 - {}^{10}\log H)$

For 20°C : $pF = 6.5020 + {}^{10}\log (2 - {}^{10}\log H)$

For 25°C : $pF = 6.5094 + {}^{10}\log (2 - {}^{10}\log H)$

E. Vapor pressure method with controlled relative humidity

In this method a soil sample is allowed to reach moisture equilibrium with a known air humidity. Constant humidity can be realized over a salt solution or over a mixture of , for example, sulfuric acid or glycerol and water.

Saturated salt solutions in contact with its undissolved salt do not change in concentration with the adsorption of water, this in contrast with unsaturated salt solutions or mixtures of sulfuric acid or glycerol and water.

On the other hand the influence of changes in temperature on the relative humidity, obtained with most saturated salt solutions, is usually larger than with unsaturated salt solutions or mixtures of sulfuric acid or glycerol and water.

For most non-saline soils the vapor pressure method can be used to check certain values that are obtained with the pressure membrane apparatus (e.g. the 15 atm. percentage). Moreover the vapor pressure method is well suited to hysteresis determinations.

The relation between suction (pF) and relative humidity has already been mentioned (moisture retention curves - Section D).

In the range pF 5.0 - 4.5 determinations must be carried out in a temperature-controlled room, whereas at suctions below pF 4.5 very accurate temperature control ($<0.01^{\circ}\text{C}$) is essential.

Apparatus. Water-thermostat (Tamson T.V. 40, temperature constancy $\pm 0.005^{\circ}\text{C}$), Beckmann thermometer (range 5°C , scale division 0.01°C), thermometers (accuracy 0.01°C , with certificate of Standards), stainless steel small-mesh wire baskets (diameter approx. 20 mm, height 10 mm), vacuum Erlenmeyer flasks with rubber stoppers, tubes, waterjet pump, analytical balance (accuracy 0.1 mg), drying oven, desiccator with silicagel.

Reagents. The following saturated salt solutions of which the change in solubility with the temperature is relatively small can be recommended for maintaining a constant relative humidity:

Saturated salt solution	Relative humidity (%) at 20°C	pF
Ammonium oxalate $(\text{NH}_4)_2 \text{C}_2\text{O}_4 \cdot \text{H}_2\text{O}$	98.8	4.2
Potassium sulfate K_2SO_4	97.1	4.6
Potassium chromate K_2CrO_4	88.0	5.2
Sodium chloride NaCl	75.8	5.6
Potassium carbonate $\text{K}_2\text{CO}_3 \cdot 2\text{H}_2\text{O}$	44.0	6.0

Procedure. Put in the vacuum-Erlenmeyer flask some of the salt selected and add some distilled water thus obtaining a pulpy mixture.

If necessary, moisten part of the sample with distilled water using a vaporizer until it is sufficiently wet to obtain the equilibrium value in the drying condition, the remainder may have to be dried first in order

to obtain the equilibrium value in the wetting condition.

Transfer some of both dry and wet soil each into a separate wire basket and weigh. Suspend the baskets inside Erlenmeyer flasks containing the same salt-water mixture and attach the flasks to a stand made to fit inside the thermostat vessel. Place the stand with Erlenmeyer flasks inside the water-thermostat and evacuate with the waterjet-pump.

Fill the thermostat vessel with water and adjust the temperature at 25°C . Check temperatures inside the tank at various places, also verify the fluctuation in temperature with the Beckman thermometer. After three days remove the baskets with soil, weigh quickly and replace inside the Erlenmeyer flasks. Repeat weighings at 24-hour intervals to a constant weight, thus obtaining the soil moisture content in the drying condition as well as in the wetting condition.

Expose the samples to 105°C in the laboratory oven for 16 hours and weigh again, using the desiccator with silicagel for transport from oven to balance.

Calculations. For the determination of the weight percentage of moisture and conversion into volume-percentage of moisture: viz. moisture-retention curves, section C - calculations.

Remark. Experiments are carried out to weigh the baskets with soil without removal from the conditioned atmosphere.

F. Supplementary determinations

The moisture content at pF 0.4 approaches the moisture content at complete saturation (pF $-\infty$). The latter can be obtained by calculation of the total porosity from the apparent and the real specific gravity.

Determination of the apparent specific gravity (bulk density)

Apparatus. Core sampler, sample boxes, drying oven, balance.

Take the samples in stainless steel cylinders having a content of 100 cm^3 as described under moisture retention curves, section A.

Procedure. Determine the oven-dry weight of the samples by exposing sandy soils for 24 hours and clay soils for 30-48 hours to 105°C in the drying-oven.

Calculations. The apparent specific density = the oven-dry weight of the sample : 100.

Determination of the real specific gravity

a. 'Alcohol'-method

Apparatus. Sieve (2mm), mortar and pestle, grinding mill, drying-oven, desiccator, balance, volumetric flasks (50 cm³) with Teflon-stopcock.

Reagents. Ethylalcohol and iso-propylalcohol mixed in a volume ratio 1 : 1.

Preparation of the soil. If necessary, sieve the air-dry soil through a 2 mm sieve to remove stones, shells, roots, etc.

Pulverize the soil in a mortar (sand, silt) or in a grinding mill (loam, clay).

Dry the soil in the drying-oven at 105°C and allow to cool inside a desiccator with silicagel.

Procedure. Transfer approx. 5 grams of oven-dry soil into a volumetric flask (50 cm³) and weigh the flask before and after filling (resp. a and b gram, accuracy 0.01 gram). Work in duplicate.

Fill the burette with the alcohol-mixture up to the zero mark and add a few cm³ from the burette to the soil, shaking the flask slightly at the same time. Continue until a liquid soil paste has been obtained.

Rap the flask gently while revolving the paste over the inner glass surface in order to remove all entrapped air. Complete filling the flask with the alcohol-mixture until the mark, tapping the flask slightly on the table at the same time. Read from the burette the quantity of alcohol used (x cm³, accuracy 0.01 cm³).

Calculations. Real specific gravity of soil = $b-a/50-x$.

b. 'Water'-method

Apparatus. Sieve (2 mm), mortar and pestle, grinding mill, drying-oven, desiccator, analytical balance, volumetric flasks (50 cm³), vacuum exsiccator, waterjet-pump.

Preparation of the soil, as described under a.

Procedure. Transfer approx. 5 grams of oven-dry soil into a volumetric flask of 50 cm³. Weigh the flask before and after filling (resp. a and b gram, accuracy 0.001 gram). Work in duplicate.

Add distilled water (temperature t°C) to the flasks, while shaking until the water level is approx. 1 cm above the soil surface and place the flasks in a vacuum exsiccator. Evacuate the exsiccator during 2 to 3 hours by means of a waterjet-pump. Restore atmospheric conditions inside the exsiccator, complete filling the flasks with distilled air-free water until the mark, and weigh (y gram, accuracy 0.001 gram).

Calculations. Real specific gravity =
$$\frac{b - a}{50 - \frac{y-b}{d_t}}$$

d_t = density of water at temperature t°C.

Remark. The volume of the volumetric flasks must be checked at the temperature concerned.

Porosity

The porosity (total pore space = TPS) can be calculated from the formula:

$$TPS = 100 - \frac{100 \times \text{apparent specific gravity}}{\text{real specific gravity}}$$

References

- Croney, D., J.D. Coleman and P.M. Bridge. 1952. The suction of moisture held in soils and other porous materials. Road Research Technical Paper no. 24.
- Harst, G.G. van der. and W.P. Stakman. 1961. The use of the sandbox-apparatus to determine pF-curves in the range pF 0.4 to pF 2.7. Note no. 81 of the Instituut voor Cultuurtechniek en Waterhuishouding.
- Janse, A.R.P. 1954. Een eenvoudige membraanpers. Landbouwkundig Tijdschrift, 66-1; 40.
- O'brien, F.E.M. 1948. The control of humidity by saturated salt solutions. J. Sci. Instr. 25, 73-76.
- Peerlkamp, P.K. and P. Boekel. 1960. Moisture retention by soils. Proceedings of the Technical Meetings Band 14 of the Committee for Hydrological Research T.N.I.
- Richards, L.A. 1947. Pressure membrane apparatus, construction and use. Agr. Eng. 28, 451-454; 460.
- Stakman, W.P. and G.G. van der Harst. Prescription for the use of the pressure membrane apparatus. Note (in press) of the Instituut voor Cultuurtechniek en Waterhuishouding.

W.P. Stakman

The equilibrium moisture content at
various constant pF-values

The point of equilibrium between the suction (resp. pressure) applied to a soil sample and its moisture content is reached asymptotically. Whether this equilibrium is reached is generally inferred from the observation that a further decrease in weight of the sample can be neglected. The rate of approaching the equilibrium varies from sample to sample. This rate is a function of the unsaturated conductivity.

The results of the initial weighings of a sample are not often used. Still they may give valuable information with respect to the equilibrium point and the unsaturated conductivity.

The description of a method, which was developed to check the experimentally obtained equilibrium value by taking into account the complete series of weighings, is given below. The rate of approach is an extra-important indication of the soil structure.

The application of this method has for the speed of handling of the samples in the laboratory the advantage that the time needed to reach equilibrium can be determined beforehand, avoiding unnecessary weighings. As to the final suction value (pF 2.7) it is not essential to wait for the attainment of the equilibrium, so that the experiment can be finished at an earlier stage.

A simplified formula

When using cylinders of 100 cm^3 content the outflow $Q(t)$ equals the change in moisture content $M(t)$ (say) and is also identical to the change in total weight of the sample.

Making use of the equation for the one-dimensional vertical flow (viz. capillary conductivity pag. 14) and lumping together the constants, yields the following simple formula for the relation between $M(t)$ and t :

$$M(t) - M_{\infty} = Ae^{-B^*t} \quad (1)$$

where:

$M(t)$ = moisture content at time t after application of suction

M_{∞} = equilibrium moisture content ($t \rightarrow \infty$)

A and B^* being constants

$$B^* = \frac{K}{B} \frac{\alpha^2}{l^2} \quad (\text{see pag.14})$$

K = capillary conductivity

B = slope of desorption curve at value of stress

α = constant

l = length of sample.

For $t \rightarrow \infty$, $M(t) = M_{\infty}$, so M_{∞} is the asymptotical value of $M(t)$ being the moisture content of the soil sample when equilibrium has been reached. Now let $\frac{\ln A}{B^*} = A'$ with \ln as notation for logarithms to base e , equation (1) then becomes:

$$M(t) - M_{\infty} = \exp. \left\{ - B^* (t - A') \right\} \quad (2)$$

Plotting $M(t)$ on the vertical ordinate and t on the horizontal gives after translation of $M(t)$ over a distance M_{∞} and t over a distance A' the fundamental form:

$$M'(t) = e^{-B^*t'} \quad (3)$$

('the prime indicating translation has taken place)

For each value of B^* , the one-parameter family of curves, given by function (3), yields a curve with the horizontal ordinate as asymptote for values of t approaching infinity.

The parameter B^* determines the curvature and is at the same time a measure for the velocity, with which the water is drawn from the sample and bears a direct relation to the capillary conductivity.

For $t = 0$ the value of $M'(t)$ is independent of B^* , so all the curves pass through the centerpoint $(0,1)$.

In order to facilitate accurate interpretation of the nomogramme the scale of the vertical ordinate is enlarged with a factor $2e$. The general function of the family of curves (3) is now modified into the mathematical expression:

$$y = (2e)e^{-\frac{1}{2}bx}$$

Now all curves pass through the centerpoint $(0,2e)$ (fig. 4).

The relation between the variables of equation (4) and (1) to (3) is

$$y = M(t) - M_{\infty} = M'(t)$$

$$x = t - (B^*)^{-1} \ln A/2e = t - A' + \frac{\ln(2e)}{B^*} = t' + \frac{\ln(2e)}{B^*}$$

$$b = 2 B^*$$

Procedure

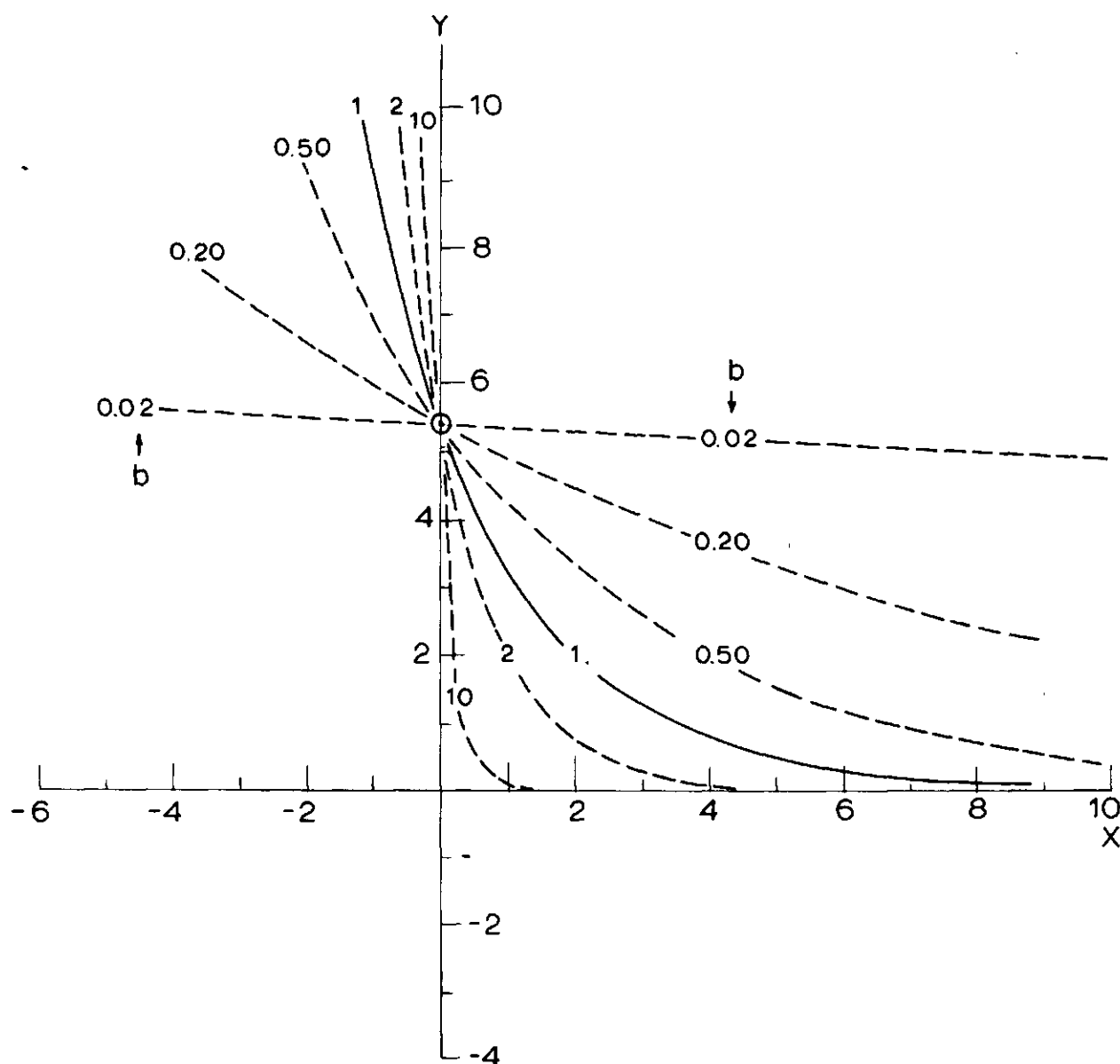
Plot the weighing results (grams) against time (days) on transparent graph paper. Shift this paper over the nomogramme, ensuring that the ordinates of both remain parallel, thus enabling the selection of the curve fitting in best with the experimentally obtained points. The most suitable method is to select visually that curve from the nomogramme for which the sum of the deviations, measured perpendicularly to this curve, becomes zero. The point of intersection of the asymptote of the nomogramme and the vertical ordinate on the transparent graph paper yields the equilibrium weight.

Because of the shape of the curve it is essential to determine the time of weighing accurately during the early period after having applied a certain level of suction. This accurate determination of the time intervals is needed to establish the horizontal translation. When the loss of moisture decreases, the influence of time on the accurate determination of shape and location of the curve diminishes. From a certain time onward accurate weighing is of main importance to fix the location of the asymptote. The value of

fig. 4

PART OF AN e - FUNCTION - NOMOGRAMME BASED ON THE RELATION:

$$Y = (2e) \exp\left(-\frac{1}{2} bx\right)$$



⊙ = centerpoint

B* belonging to the curve used gives the relative value for the capillary conductivity.

Remark. An example of grafical analysis of the relation between time and weight is given in figure 5. The successive weighing data resulting from the application of a suction have been found to conform to formula (3).

References

- Rijtema, P.E. 1959. Calculation of capillary conductivity from pressure plate outflow data with non negligible membrane impedance. Technical Bulletin 12 of the Instituut voor Cultuurtechniek en Waterhuishouding
- _____ 1959. De formule van het vochtverlies van een pF-monster. Stencil of the Instituut voor Cultuurtechniek en Waterhuishouding
- Stol, Ph.Th. An e-function nomogramme as aid to the determination of the equilibrium moisture content and the capillary conductivity of soil samples (in press)

Ph.Th. Stol

fig. 5

APPLICATION OF THE e -FUNCTION NOMOGRAMME TO THE
WEIGHING RESULTS OF A CLAYEY MARINE SAND AT $pF=2,7$

