

Instituut voor Cultuurtechniek en Waterhuishouding  
Wageningen

**ALTERRA**

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CALCULATION OF CAPILLARY CONDUCTIVITY AND CAPILLARY RISE  
FROM GRAIN SIZE DISTRIBUTION

V. COMPARISON WITH THE BROOKS AND COREY METHOD

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I N H O U D

	b1z.
1. INTRODUCTION	1
2. THE BROOKS AND COREY METHOD	2
3. THE CALCULATION OF THE PARAMETERS IN THE BROOKS AND COREY FORMULA FROM TEXTURAL PROPERTIES	4
4. THE INFLUENCE OF ORGANIC MATTER CONTENT ON THE VALUE OF THE EXPONENT $n$ IN BROOKS AND COREY'S FORMULA	7
5. SATURATED CONDUCTIVITY AS DERIVED FROM MOISTURE RETENTION CURVES COMPARED TO MEASURED VALUES	13
6. SUMMARY AND CONCLUSIONS	16
REFERENCES	18

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1. INTRODUCTION

A considerable lot of work has recently been done to develop a method to calculate capillary conductivities and capillary rise of soils from the granular composition. This method uses the Brooks and Corey formula and the values of the parameters in it are calculated from textural properties by means of simple functions which are empirically determined (BLOEMEN, 1977, I, II, III, IV). This method has some advantages over the Brooks and Corey method as initially conceived, deriving the value of the parameters in the formula from the moisture retention curves. (BROOKS and COREY, 1964). Especially for practical purposes the quick availability of the results of the calculation from textural properties is of great advantage. It proceeds from the big difference between the two methods as concerns the time required for both sampling and analysing. It is clear however that a moisture retention curve is a more complete characterization of the soil than a granular composition. The pore size distribution, which is reflected by the moisture retention curve, is not only depending on the granular composition, but just as well on organic matter content and density (RENGER, 1971). Structure so far as it is not related to these properties may have an independent effect on pore size distribution. Carbon dioxide content is perhaps also connected.

Before it can be substantiated that capillary properties of soils can as well but quicker and cheaper be calculated from the granular composition in stead of the moisture retention curve, both methods have to be compared.

In the following paragraphs such a comparison is based on the data of a number of samples of which both the granular composition

and the moisture retention curve was known, as well as the organic matter content and the weight by volume. These data were partly taken from the archives of the Institute for Soil and Water Management, partly provided by the Netherlands Soil Survey Institute.

It is shown to what extent the values of the parameters in the Brooks and Corey formula, as derived in both ways, agree. A distinctive effect of organic matter content in this matter is demonstrated.

## 2. THE BROOKS AND COREY METHOD

The formula of Brooks and Corey for the calculation of hydraulic conductivity  $k(\psi)$  in cm per time unit is

$$k(\psi) = k_s \left( \frac{\psi_a}{\psi} \right)^n \quad \psi > \psi_a \quad (1)$$

Here  $k_s$  is the permeability of saturated soil in cm per time unit,  $\psi_a$  is the air entry potential in centimeters and a measure of the largest pore size in the soil. The exponent  $n$  has a linear relation with a pore size distribution index  $\lambda \cdot k(\psi) = k_s$  if  $\psi < \psi_a$ .

The values of the parameters in eq (1) are derived from the relation between soil water content and suction. The concept of residual saturation  $S_r$  is introduced, referring to the amount of water which does not contribute to capillary flow at high tensions because during the drying process it remains behind in isolated spots. It is found as the specific value of  $S_r$  which gives a linear relation when  $\log \frac{S-S_r}{1-S_r}$  is plotted against  $\log \psi$ . Now

$$\lambda = \frac{d\left(\log \frac{S-S_r}{1-S_r}\right)}{d(\log \psi)} \quad (2)$$

and according to theory

$$n = 2 + 3\lambda \quad (2a)$$

The air entry potential  $\psi_a$  is considered to be approximated by the intersection point of the straight line with the slope  $\lambda$  and the log  $\psi$  scale.

According to Brooks and Corey (1964)  $k_s$  should be determined experimentally. LALIBERTE, BROOKS and COREY (1968) however give an equation for the calculation of permeability of the saturated medium, viz.

$$k_s = \frac{Pej2\lambda}{5\psi_a^2(\lambda+2)} \quad (3)$$

Pe is the effective porosity, calculated as  $Pe = P(1-S_r)$  from porosity P. j is the surface tension of water ( $74 \cdot 10^{-7}$  J.) and l cm of air entry value  $\psi_a$  is  $9.80665 \cdot 10^{-7}$  Pa. Eq. (2) calculates  $k_s$  in  $\text{cm}^2$ . Conversion to  $\text{cm} \cdot \text{sec}^{-1}$  is effected by multiplying with  $g/v$ , where g is acceleration of gravity ( $980.665 \text{ cm} \cdot \text{sec}^{-2}$ ) and v is kinematic viscosity ( $0.01297 \text{ cm}^2 \cdot \text{sec}^{-1}$ ).

The derivation of the parameters  $\lambda$  and  $\psi_a$  in the Brooks and Corey formula is clearly based on an idealized general form of the soil moisture content vs suction relation, rousing the expectation of easy determination. In practice the experience is that the method gives a great deal of difficulties. There are three causes for this,

1. from a methodological point of view the determination of moisture retention curves is inaccurate when samples are repeatedly removed from a porous sandbed for weighing and at higher tensions disturbed instead of undisturbed samples are subjected to pressure instead of suction to remove the water. The retention curves used in this study have been determined in this way.

2. BOUMA (1977) reviews the many problems associated with estimating a pore size distribution from moisture retention data and states that estimates of real pore-size distributions from desorption curves are erroneous. Sorption data give better estimates of pore size distributions in sandy soils. In clayey soils the capillary model is irrelevant. Bouma explains why it is important to refer always to 'equivalent' pore size distribution.

3. Moisture retention curves do not always comply with the idealized concept used by Brooks and Corey. An extensive set of 385 moisture retention curves collected by ANDERSSON and WIKLERT (1972) demonstrate how light as well as heavy soils may have a very capricious course very different from the smooth course presumed by Brooks and Corey. Also in many cases the air entry potential seems to be poorly defined on the curves. BRUCE (1972) states the same for a clay loam and a sandy clay loam and also reports the difficulty experienced in such cases with the Brooks and Corey method.

It is not the intention of this paper to examine the Brooks and Corey method. The foregoing items are given to emphasize that the value for the exponent  $n$  and  $\psi_a$  in eq (1), which are derived from a number of moisture retention curves, may have a considerable error. These values, given in table 1, are determined from desorption curves, using the graphical technique, suggested by Brooks and Corey. The data points available on these curves were determined at suctions of  $2\frac{1}{2}$ , 10,  $31\frac{1}{2}$ ,  $(63)^*$ , 100, 200, 500 and 2510 cm. It is virtually unavoidable that the values of  $\lambda$ ,  $n$  and  $\psi_a$  entered in table 1 are to some extent subjective and arbitrary. Of course this has its effect on the values of  $k_s$ , calculated with eq (3), which are also given in table 1.

### 3. THE CALCULATION OF THE PARAMETERS IN THE BROOKS AND COREY FORMULA FROM TEXTURAL PROPERTIES

The textural properties from which capillary conductivities of soils can be calculated are the median grain size  $M_d$  and an index  $f$  for the grain size distribution.

In the index  $f$  the percentage of particles  $<2 \mu\text{m}$  has a strong influence but is not predominant (BLOEMEN, 1977II). It shows a close

\*Only the Netherlands Soil Survey Institute

Table 1. Some physical data from a number of soil samples and values of  $\psi_a$ ,  $\lambda$  and  $k_s$  calculated from textural properties as well as derived from moisture retention curves

Nr.	Organic matter %	Weight by volume gr/100 cc	f	$M_d$ mm	$\psi_a(f, M_d)$ cm	$\lambda(f)$	$k_s(f, M_d)$ cm.day <sup>-1</sup>	$\psi_a(pF)$ cm	$\lambda(pF)$	$k_s(\lambda, \psi_a)$ cm.day <sup>-1</sup>
1	8.3	119	0.81	75	39	0.41	97	44	0.31	237
2	8.2	115	0.80	80	36	0.41	111	28	0.27	542
3	5.1	128	0.77	75	38	0.39	101	28	0.27	437
4	1.3	151	0.77	95	30	0.39	159	39	0.63	412
5	0.3	179	0.60	80	33	0.30	137	22	0.17	365
6	13.9	85	0.78	100	29	0.39	174	20	0.23	1 155
7	5.5	122	1.16	145	28	0.63	266	43	0.40	289
8	0.1	159	1.68	160	34	0.97	244	27	0.98	1 040
9	0.1	168	1.85	135	42	1.10	164	49	1.25	379
10	0.2	160	1.71	135	40	1.01	174	57	1.11	149
11	0.1	166	1.92	165	36	1.16	235	39	1.47	717
12	4.7	141	0.74	105	26	0.38	199	36	0.23	249
13	15.6	95	0.55	60	36	0.27	84	52	0.20	155
14	10.5	116	0.69	48	53	0.35	46	20	0.10	487
15	0.1	152	2.08	86	72	1.31	63	60	1.59	349
16	6.2	129	1.11	140	28	0.60	257	40	0.25	247
17	0.2	171	2.67	165	47	1.77	184	46	2.03	621
18	1.4	171	0.96	115	30	0.50	196	40	0.55	338
19	0.2	169	2.37	165	43	1.57	201	49	3.26	637
20	3.4	150	0.81	110	27	0.42	204	61	0.24	85
21	6	126	1.71	135	40	1.01	174	32	0.21	353
22	2	142	2.15	140	46	1.37	157	49	1.70	656
23	17.4	96	1.62	140	37	0.95	194	47	0.40	337
24	0.7	162	1.20	115	35	0.66	166	70	1.76	266
25	19.5	75	0.90	105	31	0.47	172	31	0.19	491
26	9.6	117	0.97	125	28	0.51	228	41	0.37	337
27	14.6	101	0.92	115	29	0.48	202	45	0.24	209
28	31.7	35	0.65	110	23	0.33	240	30	0.14	439
29	0.5	162	1.53	170	30	0.88	295	24	1.63	2 321
30	8.9	114	0.80	125	24	0.41	263	47	0.44	325
31	6.8	111	0.70	100	26	0.35	189	55	0.54	250
32	0.6	186	0.39	38	42	0.19	45	38	0.23	162
33	0.5	172	1.21	130	32	0.66	209	29	0.70	758
34	13.1	106	0.38	115	14	0.18	388	9	0.17	4 145
35	6.6	129	1.25	120	35	0.69	175	21	0.50	1 690
36	13.9	96	0.65	80	31	0.32	130	29	0.24	572
37	4.1	142	0.65	49	49	0.33	50	40	0.25	238
38	12.5	100	0.64	100	25	0.32	202	34	0.26	430
39	6	135	1.92	145	41	1.18	183	22	0.62	1 688
40	1.4	167	2.22	145	46	1.43	165	50	1.15	393
41	11.1	109	2.09	155	41	1.32	196	30	0.51	926
42	0.6	186	0.63	55	43	0.31	64	55	0.38	123
43	3.2	138	1.95	140	43	1.20	169	22	0.82	2 156
44	8.1	129	1.57	140	36	0.91	199	40	0.53	459
45	0.6	147	1.81	170	33	1.09	260	17	0.90	3 042
46	1.3	131	2.22	135	48	1.43	143	23	1.23	2 472
47	0.4	169	1.10	125	31	0.59	208	30	1.00	1 215
48	0.6	158	1.19	190	22	0.65	440	22	0.55	1 262
49	0.9	151	0.58	100	22	0.29	217	20	0.18	622
50	1.4	156	0.21	29	34	0.10	42	34	0.18	215
51	0.5	156	1.32	390	12	0.73	1631	8	1.21	20 375
52	3.3	141	1.99	95	63	1.23	79	17	0.59	2 925
53	2.2	143	0.20	6	146	0.09	2	90	0.22	44
54	0.5	159	1.93	200	30	1.18	339	27	1.55	1 833
55	0.3	164	2.22	195	35	1.43	291	34	1.67	876
56	0.3	149	2.81	185	44	2.00	221	30	1.49	1 414
57	0.7	185	0.76	115	29	0.39	232	28	0.14	186
58	0.9	163	0.89	100	32	0.46	158	45	0.44	223
59	1.0	153	1.54	120	41	0.89	150	79	0.53	85
60	0.3	164	2.48	165	44	1.67	194	28	1.22	1 297
61	0.6	166	1.54	355	15	0.89	1214	19	0.99	2 530

relationship with the exponent  $n$  in the Brooks and Corey formula, as read from the slopes of a number of  $k$  vs  $\psi$  relations taken from literature. In fig. 1 the diagram is shown in which the  $f$  vs  $n$  relationship was demonstrated. It has been used to read from an estimated curve the values of the exponent  $n$  for undisturbed soils corresponding with calculated  $f$ -values. It has to be recommended however to make  $n$  computable from  $f$ . Therefore the best fitting curve in fig. 1 has been determined. The condition was made that the

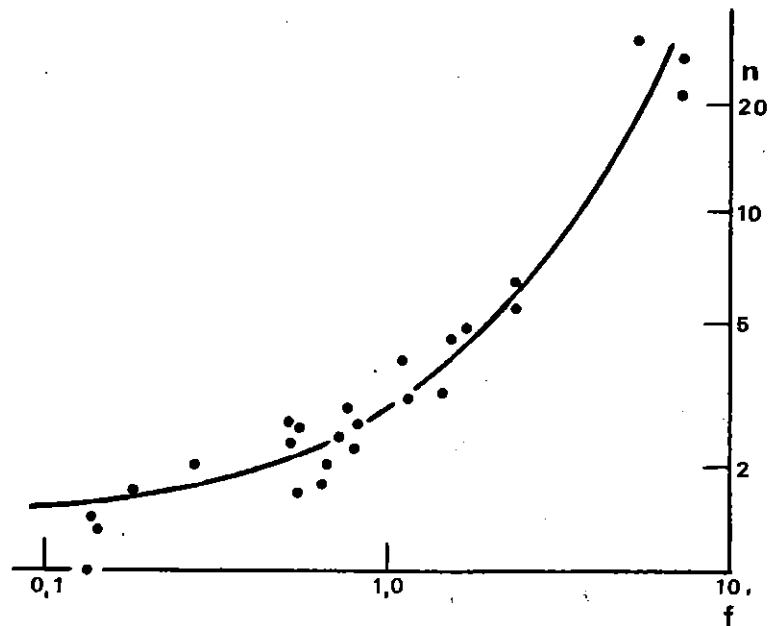


Fig. 1. Relationship between grain size distribution index  $f$  and the exponent  $n$  in Brooks and Corey's formula, valid for undisturbed soils

minimum value of  $n = 1.4$ . This minimum has been fixed on the grounds of an analysis of the regression between the exponent  $n$  as determined by the Brooks and Corey method from moisture retention curves, and accordingly having a theoretical minimum of 2.0, and as read from the measured  $k$  vs  $\psi$  relations of the same soils. It appeared that though the theoretical values of the Brooks and Corey method are



proportionate with measured values, they are systematically too high with 0.6 (BLOEMEN, 1977I). So

$$n = 1.4 + 3\lambda \quad (2b)$$

Now the best fitting curve in fig. 1, determined with the method of least squares is

$$n = 1.4 + 4.536 (e^{0.3f} - 1) \quad (4)$$

$$\text{so } \lambda = 1/3 \times 4.536 (e^{0.3f} - 1) \quad (5)$$

In table 1 the values of the index  $f$ , as calculated from the granular composition, and the median grain size  $M_d$  are given. Besides the values of  $\lambda$ ,  $\psi_a$  and  $k_s$  are entered as calculated from  $f$  and  $M_d$ . For the calculation of  $\lambda$  the eq. (5) has been used. For the calculation of  $\psi_a$  and  $k_s$  equations were used which had been experimentally determined (BLOEMEN, 1977III). There are

$$\psi_a = 2914 f^{0.79} M_d^{-0.96} \quad (6)$$

and

$$k_s = 0.02 f^{-0.94} M_d^{1.93} \quad (7)$$

The main objection to this empirical method is that the granular composition is not a complete characterization of a soil. The gravity of this objection will probably be strongly depending on the nature of the soil.

#### 4. THE INFLUENCE OF ORGANIC MATTER CONTENT ON THE VALUE OF THE EXPONENT $n$ IN BROOKS AND COREY'S FORMULA

The data in table 1 bear on a number of soil samples varying in both granular composition and organic matter content. Because complete granular analyses, with particles  $< 2 \mu\text{m}$  determined, were needed to calculate  $f$ , the disposable material was limited.

Besides a part of it was not used because it appeared to be unrealistic to try and determine parameters in the Brooks and Corey formula from those moisture retention curves which were obviously poorly represented by the data points.

When the values of  $k_s$  are calculated with eq. (3) they are indirectly derived from the moisture retention curve. Errors in the derivation of  $\psi_a$  and  $\lambda$  will propagate into this calculated  $k_s$ . Therefore the agreement between  $\lambda$  as well as  $\psi_a$ , as derived from the moisture retention curves according to the Brooks and Corey method and as calculated from granular composition with resp. eq. (7) and eq. (6) will be looked at in the first place. In fig. 2 both values of the two properties are plotted against each other.

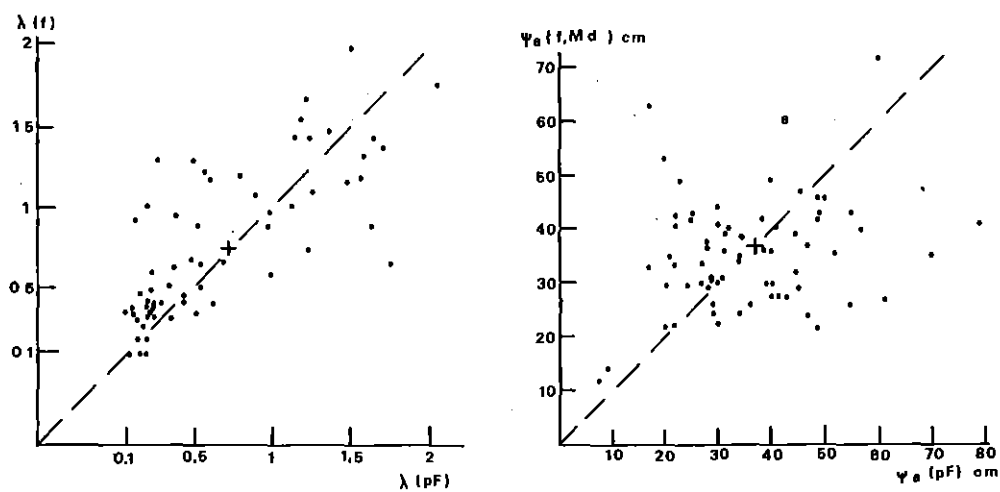


Fig. 2. Pore size distribution index  $\lambda$  (a) and air entry values  $\psi_a$  (b) as derived from moisture retention curves, plotted against values of the same properties, as calculated from the granular composition

In both cases the means of both values do not differ much but the scatter is large. Even if regression lines of the kind  $y = ax$  are

calculated in both cases correlation is poor. For the air entry potential it holds that

$$\psi_a(f, M_d) = 0.931 \psi_a(pF)$$

and for the index

$$\lambda(f) = 0.929 \lambda(pF)$$

Regression coefficients are 0.49 and 0.77 respectively.

The scatter in the diagrams in fig. 2 may be caused by other properties than  $f$  and  $M_d$  alone. These properties may influence the moisture retention curve and thus appear in the values of  $\psi_a(pF)$  and  $\lambda(pF)$ . If so the differences between  $\psi_a(f, M_d)$  and  $\psi_a(pF)$  as well as those between  $\lambda(f)$  and  $\lambda(pF)$  should show a relation with the properties concerned. The only properties, other than  $f$  and  $M_d$ , which are determined are the organic matter content and the weight by volume. These are strongly related, as fig. 3 shows.

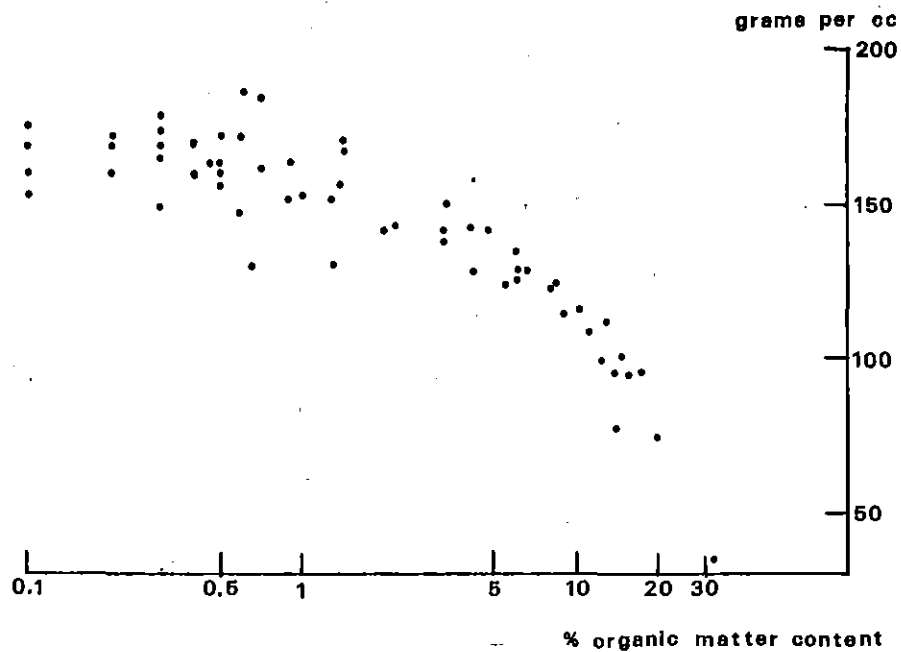


Fig. 3. Relation between organic matter content and weight by volume of the samples collected in table 1

As the weight by volume is clearly depending on the organic matter content, the latter is plotted against  $\psi_a(pF) - \psi_a(f, M_d)$  and  $\lambda(pF) - \lambda(f)$ . This shows the scatter in fig. 2b to be independent of the organic matter content. As the calculation of  $\psi_a(f, M_d)$  is based on measurements of  $\psi_a$  the scatter in fig. 2b must be assumed to be partly the result of  $\psi_a$  being poorly defined on a large part of moisture retention curves. This conclusion agrees with a former experience, when measured  $k-\psi$  relations were compared with those calculated from moisture retention curves, showing over- and under-estimation of  $\psi_a$ , as derived from the moisture retention curves (BLOEMEN, 1977, I)

In fig. 4  $n(pF) - n(f)$ , calculated as  $3\{\lambda(pF) - \lambda(f)\}$  is plotted against the organic matter content. Differentiation has been made according to  $f$ -values. It appears that the organic matter content is explanatory for a large part of the scatter in fig. 2c, especially when soils with high  $f$ -values are concerned. Straight lines are calculated in the separate diagrams. These lines intersect with the horizontal through  $n(pF) - n(f) = 0$  at an organic matter content of  $\pm 1\%$ . This is about the average of the samples appearing in fig. 1 so the curve in fig. 1 can be designated as valid for soils with an organic matter content of 1%. Fig. 4 shows how to apply a correction on the values of the exponent  $n$  as calculated with eq (4). Because a moisture retention curve is a more complete characteristic of the soil than a granular composition  $n(pF)$  is basically the better of the two  $n$ -values. So the correction  $c$  for organic matter content to set off against  $n(f)$  is

$$c = + a \log(\text{org. matter content}) \quad (8)$$

where  $a$  is the negative of the slope of the lines in fig. 4. These slopes are depending on the mean values of  $f$  in the separate diagram. Both magnitudes are plotted in fig. 5. The most likely relationship between the two properties is something like the curve presented in fig. 5a, because the factor  $a$  cannot be positive and will not increase infinitely in the negative. For practical reasons however it is more convenient to use a straight line.

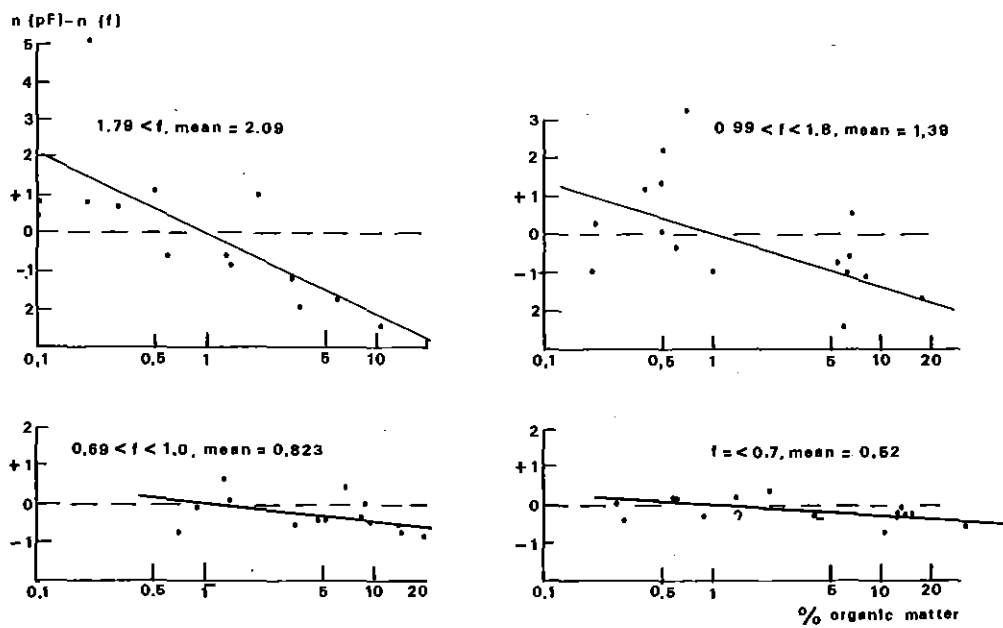


Fig. 4. The differences between the exponent  $n$  as derived from moisture retention curves and as calculated from grain size distribution index  $f$  plotted against organic matter content

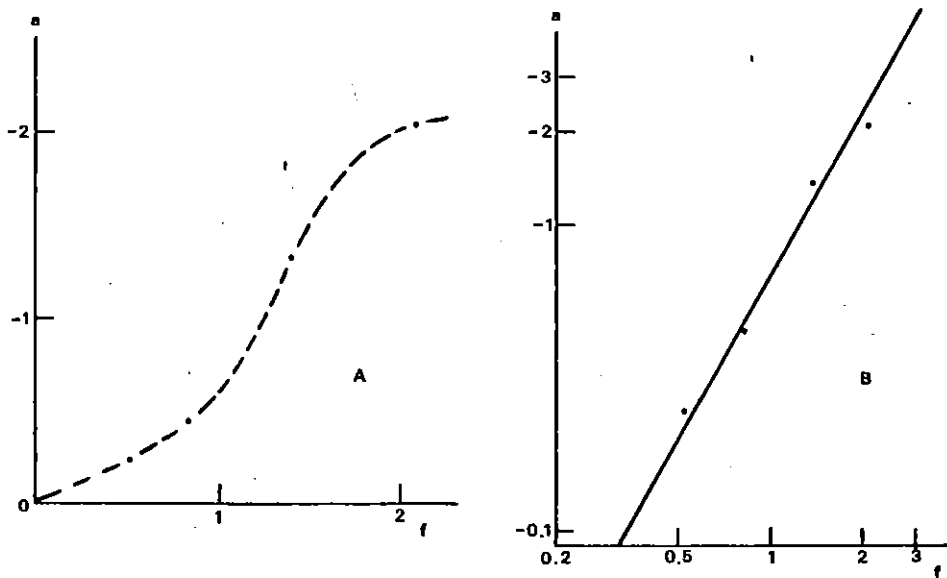


Fig. 5. Relation between the negative of the slopes (a) of the straight lines and the mean f-values in the separate diagrams in fig. 4

To prevent the calculated factor a becoming positive at low values of f a straight line on log-scales is used, like in fig. 5b. According to this line it holds that

$$a = -0.65f^{1.765} \quad (9)$$

With the equations (4), (8) and (9) the exponent n in the Brooks and Corey formula can be calculated as a function of granular composition and organic matter content.

5. SATURATED CONDUCTIVITY AS DERIVED FROM MOISTURE RETENTION  
 CURVES COMPARED TO MEASURED VALUES

In fig. 6  $k_s$  calculated with eq (3) is plotted against  $k_s$  calculated with eq (7). The data are from table 1. A regression line is calculated which satisfies the equation

$$k_s(\psi_a, \lambda) = 4.17 k_s(M_d, f)^{0.95}$$

The correlation is poor,  $r = 0.57$ . The most striking aspect of fig. 6 however is that  $k_s$ , calculated according to LALIBERTE, BROOKS and COREY is considerably higher than  $k_s$ , calculated from the granular composition. Fig. 6 is not a very objective judgement of the accuracy of the former of the two  $k_s$  values for though the calculation of the latter of the two values is based on measurements a misinterpretation of the data may have been possible.

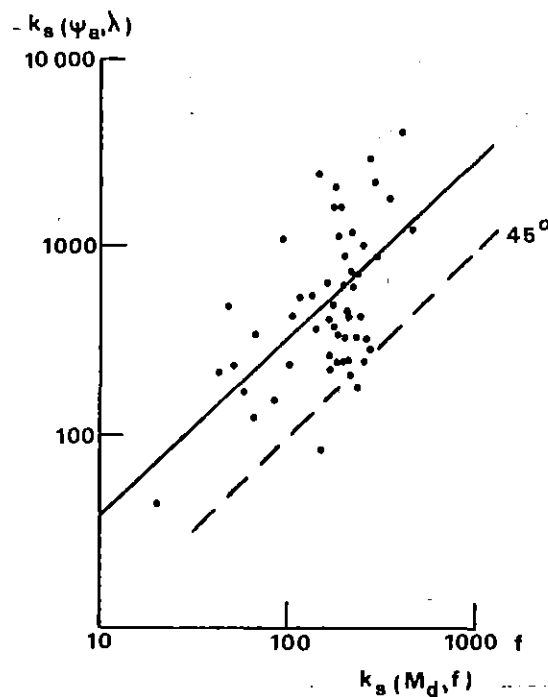


Fig. 6.  $k_s(\psi_a, \lambda)$  calculated with eq (3) plotted against  $k_s(M_d, f)$  calculated with eq (7)

Therefore  $k_s(\psi_a, \lambda)$  should be directly compared with measurements of  $k_s$ . These are not available for the specific cases in table 1.

On a former occasion measurements of air entry values  $\psi_a$  and saturated conductivities  $k_s$  were performed in 107 soil samples (BLOEMEN, 1977III). Of these samples the granular composition and the organic matter content were determined. From a part of these samples the specific weight was also determined and therefore these data can be used for a comparison of  $k_s$  calculated with eq (3) and measured values. This is because

1. air entry values are known
2. a fair estimate of the  $\lambda$ -values can be procured from calculated values of the index  $f$  using eq (5)
3. the porosities  $P$  can be calculated from the specific weights and the organic matter contents according to BOEKEL (1961). The effective porosities  $P_e$  are derived from  $P$  as shown in par. 2 with an estimated average value of residual saturation  $S_r$  of 0.10.

In table 2 the various data of the samples concerned are entered. In fig. 7 measured and calculated values of  $k_s$  in this table are plotted. They appear to be proportionate to a considerable degree but  $k_s$  calculated with eq (3) is systematically too high; at low values by a factor  $4\frac{1}{2}$  and at high values by a factor 3.

The relativity of the results of a calculation with eq (3) is obvious because for instance a slight raise of the square in the denominator in the righthandside to 2.1 already reduces  $k_s$  to about  $1/3$ . Because of the indisputableness of the general level of measured values of  $k_s$  the regression line in fig. 7 can be used to reduce  $k_s$ -values calculated with eq (3) to the correct level. About the accuracy of the separate  $k_s$ -values fig. 7 gives no information. The scatter in fig. 7 is not a measure, in the first place because  $k_s(\psi_a, \lambda)$  is calculated with measured  $\psi_a$ 's instead of  $\psi_a$ 's derived from the moisture retention curves. Fig. 2b makes clear how this may increase the scatter in fig. 7, without effecting the general level. Apart from that the effective porosities are calculated and the  $\lambda$ -values are derived from the granular composition in stead of from moisture retention curves.



Table 2. Relevant data for the comparison of measured and calculated  $k_s$ -values

Nr	f	Weight by volume gr/100 cc	Organic matter %	Calculated pore vol. %	measured $\Psi$ cm	calculated $\lambda$ -	measured $k_s^{-1}$ cm.day <sup>-1</sup>	calculated $k_s^{-1}$ cm.day <sup>-1</sup>
1	0.94	163	0.1	39	36	0.49	203.	441.
2	2.01	143	0.1	47	49	1.25	213.	561.
3	1.30	134	1.2	49	65	0.72	14.	229.
4	1.52	140	0.1	47	107	0.87	16.	93.
5	1.76	139	1.1	48	78	1.05	27.	202.
6	1.51	152	0.0	43	8	0.87	1880.	15 182.
7	1.30	150	3.0	41	19	0.72	150.	2 241.
8	0.57	137	1.2	48	76	0.28	10.5	7.
9	0.29	136	0.9	49	109	0.14	8.	20.
10	0.89	149	0.2	44	42	0.31	152.	250.
11	1.61	150	0.1	44	52	0.94	24.	388.
12	1.08	160	0.3	40	49	0.58	116.	279.
13	1.26	173	0.2	35	38	0.69	53.	463.
14	1.44	153	0.0	43	33	0.54	304.	626.
15	1.33	141	0.7	47	28	0.74	938.	1 207.
16	1.79	141	0.6	47	95	1.07	80.	135.
17	0.94	120	4.9	53	35	0.49	228.	635.
18	1.63	133	0.7	50	52	0.95	97	444.
19	1.14	131	0.6	51	59	0.62	112.	258.
20	0.97	125	0.7	53	43	0.51	100.	434.
21	2.37	169	0.4	36	34	1.57	431.	1 021.
22	3.42	158	0.2	41	31	2.71	388.	1 829.
23	2.46	150	0.1	44	50	1.65	620.	593.
24	1.68	155	0.4	42	40	0.99	166.	647.
25	1.85	167	0.4	38	44	1.12	83.	525.
26	1.71	159	0.4	40	60	1.01	250.	278.
27	1.92	168	0.2	37	27	1.18	347.	1 404.
28	0.67	157	2.1	40	80	0.34	22.	68.
29	1.09	149	0.1	44	76	0.58	55.	128.
30	2.08	148	0.1	46	80	1.31	67.	212.
31	1.34	152	0.0	43	89	0.75	59.	110.
32	1.42	169	0.4	37	42	0.80	102.	447.
33	1.93	169	0.2	37	50	1.19	197.	412.
34	2.67	171	0.2	36	40	1.86	600.	808.
35	1.94	173	0.2	35	41	1.19	161.	579.
36	0.12	110	5.5	57	150	0.06	0.4	5.5
37	0.11	104	3.7	60	90	0.05	1.1	13.5
38	0.10	95	3.3	63	93	0.05	0.9	13.2
39	0.11	107	1.7	59	152	0.05	2.2	4.6
40	0.13	104	1.3	60	202	0.06	4.1	3.2
41	0.32	152	0.9	42	45	0.15	10.	108.
42	0.35	151	0.5	43	52	0.17	15.	93.
43	0.61	155	0.5	41	80	0.30	9.	62.
44	0.20	142	0.5	46	95	0.09	32.	16.
45	0.19	138	0.2	48	145	0.09	0.4	7.
46	0.30	154	0.4	42	51	0.14	13.6	80.
47	0.21	148	0.2	44	141	0.10	11.8	8.
48	0.23	152	0.1	43	124	0.11	5.	11.

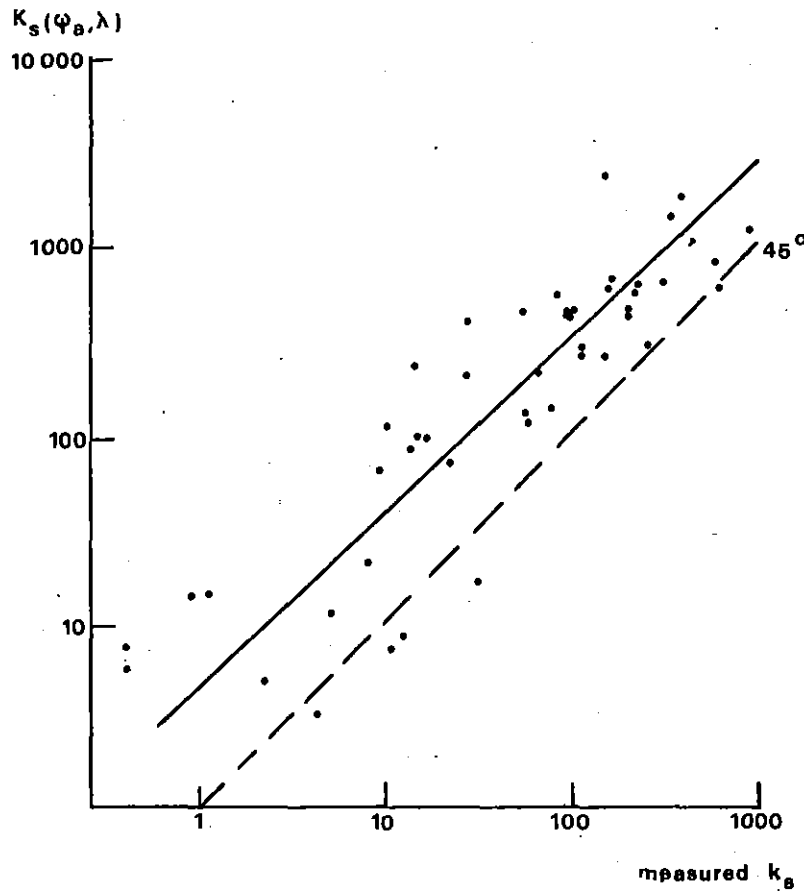


Fig. 7. Measured  $k_s$  plotted against  $k_s$  calculated with the formula of LALIBERTE, BROOKS and COREY (1968). Parameter values are not directly derived from moisture retention curves. See text

## 6. SUMMARY AND CONCLUSIONS

The values of the parameters  $\psi_a$ ,  $n$  and  $k_s$  in the Brooks and Corey formula to calculate capillary conductivities can be derived from the moisture retention curve as well as from the granular composition of the soil. Both values of the three parameters were compared. It appeared that agreement between both values of the air entry value  $\psi_a$  was poor. As the calculation of  $\psi_a$  from granular composition is based on  $\psi_a$ -measurements it was concluded that  $\psi_a$  is

poorly defined on moisture retention curves. Both values of the poresize distribution index  $\lambda$  agree better than both  $\psi_a$ -values but there is still a considerable scatter. This is partly explained by the organic matter content which appears to have an effect on pore size distribution. It is shown how the value of the exponent  $n$  can be calculated from granular composition and organic matter content. Saturated conductivity as calculated on the basis of the Brooks and Corey theory is fairly proportionate with measured values but systematically too high by a factor 3 to  $4\frac{1}{2}$ . The results of the calculation can be reduced to the correct general level on the empirical basis of fig. 7.

It is clear that the least objection to the Brooks and Corey method is that the air entry value is poorly defined on the moisture retention curves. Of more importance is that saturated conductivity is as a mean largely overestimated when it is derived from the moisture retention curve. When it is also taken into account that the theoretical minimum of the exponent  $n$  in the formula appeared to be too high with 0.6 it is clear that the theoretical approach of Brooks and Corey by itself is not suited for practical application. It needs at the least some empirical adjustment of the results. The empirical determination of the relationship between the values of the parameters in the convenient formula of Brooks and Corey and textural properties has produced such adjustment. Apart from that, this empirical approach itself has provided a usefull alternative method for the calculation of hydraulic conductivities. In a following paper it will be shown how calculated conductivities, using the Brooks and Corey method or the alternative method, agree with measured conductivities.

REFERENCES

- ANDERSON, S. and P. WIKLERT, 1972. Markfysikaliska undersökningar in odlad jord XXIII. Om de vattenhållande egenskaperna hos svenska jordarter'. Grundförbättring, 25,1972:2-3, 53-143
- BLOEMEN, G.W., 1977. Calculation of capillary conductivity and capillary rise from grain size distribution
- \_\_\_\_\_ I. Real and theoretical values of the exponent in a formula of Brooks and Corey for the calculation of hydraulic conductivities. ICW Wageningen nota nr. 952
- \_\_\_\_\_ II. Assessment of the values of the exponent in a formula of Brooks and Corey for the calculation of hydraulic conductivity from grain size distribution. ICW Wageningen nota nr. 962
- \_\_\_\_\_ III. Air entry pressure and saturated conductivity calculated from grain size distribution and median grain size. ICW Wageningen nota nr. 990
- \_\_\_\_\_ IV. Capillary rise in soiltypes and soil profiles. ICW Wageningen nota nr. 1013
- BOUMA, J., 1977. Soil survey and the study of water in unsaturated soil. Soil survey papers, no. 13. Netherlands Soil Survey Institute Wageningen
- BOEKEL, P., 1961. De bepaling van het soortelijk gewicht van grond. Instituut voor Bodemvruchtbaarheid, Groningen. Rapport IX
- BROOKS, R.H. and A.T. COREY, 1964. Hydraulic properties of porous media. Colorado State University, Hydrology papers no. 3
- BRUCE, R.R., 1972. Hydraulic conductivity evaluation of the soil profile from soil water retention relations. Soil Sci. Soc. Am. Proc. 36 nr. 4
- LALIBERTE, G.E., R.H. BROOKS and A.T. COREY, 1968. Permeability calculated from desaturation data. Journ. Irr. Drain. Division of the A.S.C.E. Vol. 94 nr. IR 1
- RENGER, M., 1971. Die Ermittlung der Porengroszenverteilung aus der Körnung, dem Gehalt an organischer Substanz und der Lagerungsdichte. Zeitschr. Pflanzenern. Bodenk. 130. 53-67