

## Characterization of Molecular Forces Influencing Seepage by Means of the pF Curve

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On the basis of the dynamical investigation of seepage through porous layers it can be stated that from among the active forces causing and maintaining water movement, gravity is the most important one. In addition to that the pressure of layers plays a significant role in great depths. In the unsaturated zone, however, the molecular forces acting between grains and water, i.e. capillarity and adhesion, should be taken into consideration.

There are some other forces counteracting the former ones. Those are the passive forces, i.e. friction (viscosity), inertial force and adhesion as well, causing the slowing down of the water movement. The passive forces are generally intensified if velocity is increased, therefore when the velocity of the movement reaches a certain value, the two kinds of forces will balance each other, and the seepage becomes a uniform flow.

As it was mentioned before, the active forces do not exert the same influence in all cases. The three main types of seepage can be separated according to the importance of the different active forces.

1. Seepage in an unsaturated layer (gravity and the molecular force are the active forces);
2. Gravitational seepage in a saturated layer (gravity is the only active force);
3. Seepage in a saturated layer followed by the compression of the layer (gravity and the pressure of the layers are the active forces).

These groups can further be divided according to the passive forces by determining, which are the main forces from among them and which can be neglected. In the case of gravitational seepage e.g. the following subdivision can be made:

- 2.1 Quadratic zone of gravitational seepage (inertia is the main passive force);
- 2.2 Transitional zone of gravitational seepage (inertia and friction are the main passive forces);
- 2.3 Zone of *Darcy's* law (friction is the main passive force);
- 2.4 Zone of microseepage (friction and adhesion are the main passive forces).

For the characterization of kinematic equations valid in the different zones of movement, some dimensionless numbers calculated as the quotient of the main active and passive forces are very suitable. Thus the general form of the equation of movement in the 2.1 group is given by the *Froude*-number ( $Fr = \text{inertia} : \text{gravity}$ ), in the transitional zone (2.2) by the ratio of the sum of inertia and friction to gravity, and, finally, *Darcy's* law can be deduced

from the *Mosonyi* and *Kovács* number ( $MK = \text{friction} : \text{gravity}$ ) [5, 8].

There are dimensionless numbers which can be determined as the quotients of the two groups of passive forces. The first group includes those passive forces which must be taken into consideration, while the ones which may be neglected belong to the second group. These numbers are suitable to determine the limits between two ranges of validity, because the extent of the zones depends on the passive forces that should be taken into account in them. Thus the *Reynolds*-number ( $Re = \text{inertia} : \text{friction}$ ) determines the limits between seepage belonging to the 2.1 or 2.2 groups and to the 2.2 or 2.3 groups as well, since at the first limit — between groups 2.2 and 2.1 — friction becomes negligible as compared to inertia; at the second limit, however, — between groups 2.2 and 2.3 — inertia, as compared to friction, may be neglected.

Similar dimensionless numbers can be formed to determine the lower limit of the validity of *Darcy's* law and to characterize seepage whose velocity is below this limit. A preliminary condition of this investigation is the knowledge and the numerical characterization of the above mentioned forces.

Further investigations of gravity, inertia and friction are not necessary because these phenomena are well-known. The two molecular forces, — adhesion and capillarity —, however, have not been studied satisfactorily although their effects are important, manifesting themselves as both active and passive forces in the case of seepage through an unsaturated layer.

The purpose of our investigation was to devise a procedure with the aid of which the numerical characteristics of these forces can be determined. It was not our intention to follow the precise investigational methods of theoretical physics, we only wished to find a suitable approximation which — in addition to characterizing the process within a predetermined range of error — should be simple and applicable in practice.

The problem was solved by using the  $pF$  curve which describes the relationship between moisture content and tension in an unsaturated layer.

### The physical model of seepage

Before characterizing the molecular forces with the  $pF$  curve, it is necessary to summarize briefly the results attained during the investigation of the seepage belonging to *Darcy's* zone or to zones of higher velocity (quadratic and transitional zones). A physical model of the stream-field could be determined by replacing the complicated network of pores between the grains with parallel pipes. The model — as it may be seen in the following — is suitable to characterize also the molecular forces and in this way a uniform system can be formed to determine the equations of movement in all zones of seepage.

Numerous efforts have been made to replace the network of pores of different sizes and of random distribution by a bunch of pipes of the same diameter. On the basis of the sizes of the substituting pipes the equation of movement can be established in that model system — e.g. in the case of a laminar movement: *Poiseuille's* equation. Thus the theoretical equations of seepage can be determined, their formerly established empirical forms can be controlled and the coefficients of the latter can be calculated (e.g. in the case of the above mentioned laminar movement: *Darcy's* law).

It is known from previous investigations that — in the case of a homodisperse sample — the pipe diameter of the substituting bunch of pipes should

be proportional to the grain-size. If the sample is heterodisperse the use of more design grain-sizes determined by the granulometric curve is proposed for characterizing the sample (e.g. HAZEN  $D_{10\%}$ , SEELHEIM  $D_{50\%}$ ). This fact indicates that these authors presumed — even if they did not mention it — that those grain-sizes were proportional to the above mentioned pipe-diameter, at least in the investigated range (e.g. in HAZEN's case if the uniformity coefficient is  $1,5 < U = D_{60\%}/D_{10\%} < 2,5$ ) [4].

The investigations of KOŽENY [6], who established that friction was proportional to the surface of grains and gravity to the volume of water, and thus — in an indirect way — to the volume of grains as well, were an important step forward to determine both the design grain-size and the relationship between the latter and the diameter of the substituting pipes. For this reason the ratio of the surface of grains to the volume of water should be the same in the original system as in the replacing one. On this basis KOŽENY determined the so-called effective diameter as a characteristic grain-size, the diameter of those spheres which, if forming a homodisperse sample, this latter has the same ratio between the surface and the volume of the grains as the investigated heterodisperse sample formed also from spheres but with different diameters:

$$D_{it} = \frac{1}{\sum_{i=1}^n \frac{\Delta S_i}{D_i}}, \tag{1}$$

where  $D_i$  = the diameter characterizing the  $i^{\text{th}}$  range between  $D_{i1}$  and  $D_{i2}$  diameters,

$\Delta S_i$  = the weight of grains within this range as compared to the total weight of the sample (Fig. 1).

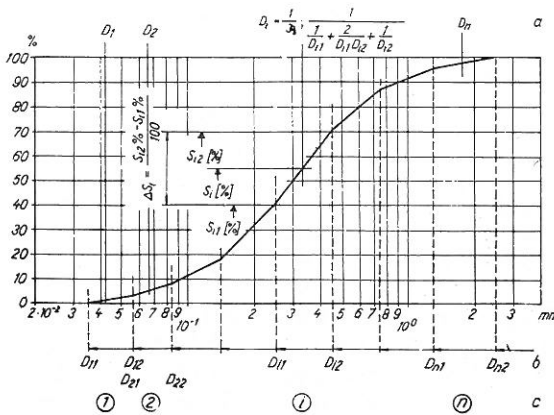


Figure 1

The symbols used for the calculation of effective diameters. a) Average diameters characterizing the intervals. b) Limits defining the intervals. c) The investigated intervals. Ordinate: percent of weight. Abscissa: Grain-size mm.

The ratio of the surface to the volume of the grains depends also on the shape of the grains. It is necessary therefore from the point of view of this

investigation to determine a shape-coefficient which can be established — based on KOŽENY's theories — as the quotient of the surface ( $F$ ) and the volume ( $V$ ) of the grains:

$$\frac{F}{V} = \frac{\alpha}{D}, \quad (2)$$

where  $\alpha$  = shape coefficient

$D$  = diameter of the sphere encircling the investigated grain.

If this shape-coefficient or its average value is known within the various intervals of the granulometric curve ( $\alpha_i$ ) the ratio of the effective diameter to the average shape-coefficient characterizing the total sample can be determined from the following equation:

$$D_{h/\bar{\alpha}} = \frac{1}{\sum_1^n \Delta S_i \frac{\alpha_i}{D_i}}. \quad (3)$$

It has to be mentioned that a quite similar result was obtained by CARMAN [1], who used directly the quotient of the surface and the volume of grains instead of the ratio expressed in equation (3). The only advantage of the latter is that it can be determined from granulometric curves and from shape-coefficients if the probable value of the latter is determined in advance by statistical investigation of numerous samples.

As the quotient of the left side of equation (3) is known, the diameter of the substituting tube ( $d_0$ ) and the number of the pipes of the model bunch to be contained in the unit cross-section of the investigated layer ( $s$ ) can be determined under two conditions. The first condition is that the ratio of the surface of the pipe-wall to the inside volume of the pipe should be the same as that of the surfaces of the grains to the pore-volume of the layer:

$$\frac{l d_0 \pi}{l d_0^2 \pi / 4} = \frac{4}{d_0} = \frac{F}{V_0} = \frac{1-n}{n} \frac{F}{V} = \frac{1-n}{n} \frac{\alpha}{D_h},$$

consequently 
$$d_0 = 4 \frac{n}{1-n} \frac{D_h}{\alpha}, \quad (4)$$

where  $V$  = the volume of the grains

$V_0$  = the volume of the pores

$n$  = porosity.

The second condition is that the cross-sectional area of the pipes within a unit cross-section should be equal to the effective free surface of the cross-section of the investigated layer which can be determined by the value of porosity. Thus the number of the pipes can be calculated from the following equation:

$$s \frac{d_0^2 \pi}{4} = n. \quad (5)$$

Thus determining the pipe-diameter and the number of pipes in the model, the discharge of the latter in the case of laminar movement can be calculated by *Poiseuille's* equation and in this way the coefficient of perme-

ability of the substituting bunch of pipes can be determined as well. This value — as compared to the results of some very precise measurements (ZUNKER [16], LINDQUIST [7], CARMAN [1]) — is 2,5 times greater than the effective coefficient of permeability of an investigated sample. The difference may be caused by three facts:

- the cross-section of the channels between the grains is not circular;
- the channels are longer than the length of the sample;
- the size of the cross-section along the channels is not a constant value

while the pipe is constituted from diffusors and confusors.

The divergence from the circular shape can be taken into account and corrected by using a coefficient the value of which is between 1,2—0,8 (FORCHHEIMER [4], ENGELHARDT [3]). Thus, apparently, it can affect but very slightly the above mentioned difference.

CARMAN [1], when investigating the process, tried to explain it by the fact that the channel is longer than the sample. In our opinion the third explanation seems to be the most probable one because in this way the non-laminar seepage can also be characterized. LINDQUIST pointed out that the ratio of the widest cross-section to the narrowest one of the channels may be even 10 but this quotient is an extreme value characterizing only one point of the channel. The discharge of a pipe constituted from short sections of two kinds of pipes with different diameters can be calculated, however, as the function of  $d_1$  and  $d_2$  diameters. There is also another condition for determining the relationship between  $d_1$  and  $d_2$ , namely, that the pipe constituted from different sections should have the same inside volume as the model pipe having  $d_0$  diameter. The decrease in the discharges of pipes (composed of two sections with different sizes) as a function of the ratio of the two cross-

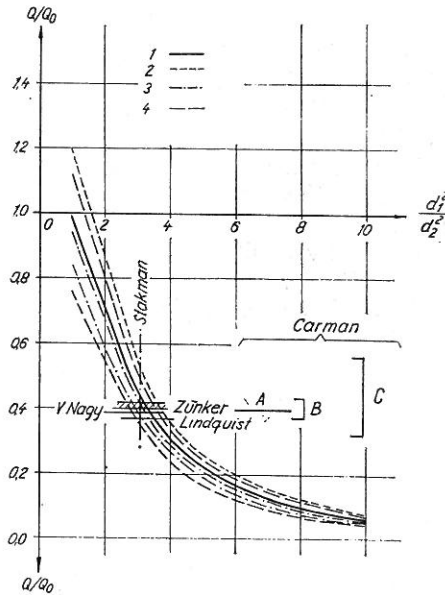


Figure 2

Decrease of discharges of pipes composed of two sections with different sizes as a function of the ratio of the cross-sectional areas as compared to the discharge of circular-shape pipes having constant diameter. 1. Circle. 2. Equilateral triangle. 3. Ellipse ( $a/b = 2$ ,  $a/b = 10$ ). 4. Rectangle ( $a/b = 1$ ,  $a/b = 10$ ). A) Mean value. B) Scattering in the case of spherical grains. C) Scattering in the case of sheet-shaped grains

sectional areas ( $d_1^2/d_2^2$ ) is shown on Figure 2. It can be finally stated that if this ratio becomes  $3 \sim 3,5$  then — almost independently of the shape of the pipes — the discharge will be 2,5 times smaller than in the case of a circular pipe with a constant  $d_0$  diameter.

Summing up what has been stated, the physical model of an investigated layer may be a bunch of pipes characterized by an average diameter  $d_0$  calculated from equation (4) and containing  $s$  number of pipes in the unit of the

cross-section (equation 5) inferring furthermore that the pipes are constituted from sections of  $d_1$  and  $d_2$  diameters. The relationship between the above mentioned diameters can be determined from the following equations:

$$d_2 = 1,86 d_1; \quad d_1 = \frac{d_0}{1,5}; \quad d_2 = 1,25 d_0. \quad (6)$$

### Characterization of the different sections of the $pF$ curve

The  $pF$  curve — generally known and used — describes the relationship between the moisture content of the investigated sample ( $W$ ) and tension ( $\psi$ ). The latter is characterized by the logarithm of the length of the equivalent water column in cm. If the tension were also plotted in an arithmetical scale, the distribution of the moisture content in the profile above the ground water would be shown by this curve. This fact explains why three sharply differing sections may be distinguished on the  $pF$  curve. The profile of the moisture content has three zones. The lower one is the closed capillary zone, it is followed by the open capillary zone and in the upper zone the moisture content is not influenced by capillarity.

As it can be seen on the curve shown as an example (Figure 3) and constructed on the basis of 105 measurements, the upper section is almost vertical. An approximately horizontal section follows it and then the curve ends with an almost vertical line. The position of the latter depends on the field capacity of the sample. If its value is smaller than that of porosity ( $W_{fc} < n$ ), then the maximum moisture content is characterized by field capacity, otherwise ( $n < W_{fc}$ ) by porosity.

The physical interpretation of the first and second sections can be given as follows.

The second section characterizes the height of the capillary zone. As it is known, along a solid wall where there is contact between a liquid and a gaseous medium, or between two liquid media, a tension appears which is caused by the asymmetric attraction of molecules. If the wall is an encircling one, — e.g. in the case of a capillary tube — these tensions are added up and the force generated in this way can counteract an other force, e.g. gravity. Capillary tension — this force corresponding to a unit-surface — can

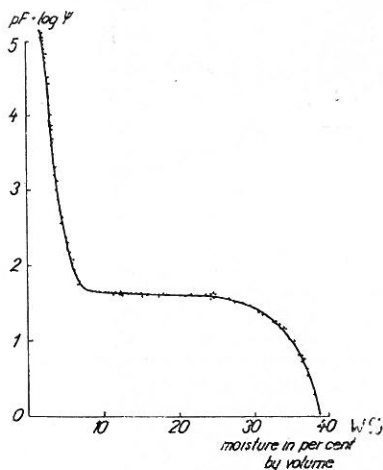


Figure 3

Water retention curve ( $pF$  curve) of a fine sand sample determined by detailed tension measurements

be measured by the height of the water column ( $h_k$ ) (rising or sinking) held by this force against gravity in a capillary tube — as compared to the level of the water table of the surrounding space.

Summarizing the results of the former investigations — if the three contacting phases are glass, water and air — a very simple equation can be

suggested to determine the capillary tension in a pipe of  $d$  (cm) diameter:

$$h_k \text{ (cm)} = \frac{0.3}{d} \quad (7)$$

In a natural soil layer the greatest part of the grains is quartz, the mineralogical character of which is similar to that of glass. For this reason the capillary head of a sample can also be characterized by equation (7). The average diameter ( $d_0$ ; equation 4) and the extreme ones ( $d_1$  and  $d_2$ ; equation 6) of the bunch of pipes chosen as a physical model are known thus — by substituting the two latter into equation (7) — the probable maximum and minimum values of the capillary head can be determined.

The approximately horizontal section of the  $pF$  curve — as the curve describes the moisture distribution in the vertical direction — also indicates those two values. The lowest point of it is at the height of the closed capillary zone while the upper one indicates the open capillary zone (the capillary head of the narrowest channels). The section between these two points characterizes the distribution of the channels of various sizes. On the basis of the effective grain-size, shape-coefficient and porosity  $d_1$  and  $d_2$  can be calculated and the obtained values, when substituted into equation (7), give the two values of the capillary head ( $h_{k1}$  and  $h_{k2}$ ). On the other hand, if the  $pF$  curve and the porosity are known, the quotient of the shape-coefficient and the effective grain-size can be determined.

Above the capillary zone not even the narrowest channels are full of water, so it cannot be the capillary meniscus which holds the water raised

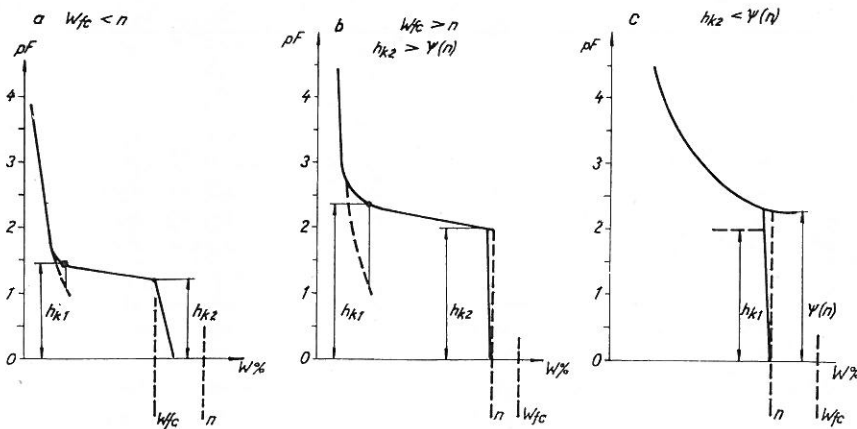


Figure 4

Notations for the explanation of the different types of  $pF$  curves

against gravity but adhesion between grains and water. Without any detailed investigations it should be mentioned here that this phenomenon is caused by the dipole character of water molecules. These molecules are polarized by the electrostatic charge of the solid wall and in this way a diffused double-layer is formed. The tension caused by this process — the so-called *van der*

*Waals* force — can be characterized in practice as a function of the distance ( $\delta$ ) measured from the wall:

$$\Psi = \left( \frac{A}{\delta} \right)^6 \quad (8)$$

On the basis of equation (8) a relationship can be determined between moisture content and tension which is, in effect, the equation of the first section of the  $pF$  curve. On the other hand, inversely, the co-efficients of equation (8) can be calculated from the  $pF$  curve.

As a first approximation, the moisture content of the sample can be determined by multiplying the grain-surface by the thickness of the film of water ( $\delta$ ) and by forming the ratio of the obtained value to the total volume:

$$W = \frac{F \delta}{V + V_0} = \frac{F}{V} \delta (1 - n) = \frac{\alpha}{D_h} \frac{A}{\varphi^{1/6}} (1 - n). \quad (9)$$

A similar result may be obtained by calculating the moisture content sticking to the walls of the model pipe-bunch and comparing this to the total volume. In a pipe of  $l$  length and  $r_0$  radius, where the inside radius of the water-film is  $r = r_0 - \delta$ , the moisture content is:

$$W_0 = l\pi(r_0^2 - r^2) = l\pi\delta(d_0 - \delta). \quad (10)$$

The surface-unit contains  $s$  number of pipes (equation 5). On the basis of the above, the relationship between moisture content and tension may be described as follows:

$$\begin{aligned} W &= \frac{s}{l} W_0 = 4n \frac{\delta}{d_0} \left( 1 - \frac{\delta}{d_0} \right) = \frac{\alpha}{D_h} \delta (1 - n) \left( 1 - \frac{\alpha}{D_h} \delta \frac{1 - n}{4n} \right) = \\ &= \frac{\alpha}{D_h} \frac{A}{\varphi^{1/6}} (1 - n) \left( 1 - \frac{\alpha}{D_h} \frac{A}{\varphi^{1/6}} \frac{1 - n}{4n} \right). \end{aligned} \quad (11)$$

The only difference between the two equations is a factor, smaller than the unit, on the right side of equation (11). Its role can be explained by the fact that the surface of grains is not plain therefore the volume of the films of water is not directly proportional to the product of surface and thickness. In the case of total saturation ( $W = n$ ) the maximum value of this factor is 0,5.

Having formulated this theoretical scheme we controlled it. Its coefficients were determined on the basis of data collected from literature and presented in Table 1. The fact that the  $W \varphi^{1/6}$  product — calculated from different data measured on the same sample — is a constant value justifies the approximation of equation (8). On supposition that the shape-coefficient does not vary essentially — its average value is 8 — the  $W \varphi^{1/6}/1 - n$  value was plotted in a bilogarithmical system as the function of the effective grain-size of the investigated samples (Figure 5).

Total saturation can be taken into account with a reducing factor (0,5) in the case of smaller grain-sizes beginning at that effective diameter the adhesion of which is equal to the capillary head belonging to the same diameter. This limit is approximately  $D_h = 8 - 10 \mu$ . The second, negative member of the reducing factor is inversely proportional to the effective diameter so if the latter is 80–100  $\mu$  the reducing factor is only 0,95 and in the case of an



effective diameter of 800–1000  $\mu$  no reduction is necessary. Accordingly, the relationship calculated from equation (10) is represented on Figure 5 by a dotted line while the full line shows the reduction according to equation (11). There is a certain difference between the theoretical relationship and the one determined by measurements, i.e. in the second case the moisture content changes with the power 0,8 of the effective diameter:

$$\frac{W \varphi^{1/6}}{1 - n} = 1.5 \cdot 10^{-3} \left( \frac{\alpha}{D_h} \right)^{0.8} \left( 1 - 5 \frac{\alpha}{D_h} \cdot 10^{-5} \right) \quad (12)$$

This can be explained by the fact that in the case of greater grain-sizes there are point-contacts between the grains but with diminishing grain-sizes the number of sheet shaped grains increases therefore the probability of sheet-contact increases as well, bringing about the decrease of the inside surface of the samples.

In the case of the investigated samples the effective diameter was greater than 5  $\mu$  so the factor ( $1.5 \cdot 10^{-3}$ ) in equation (12) is a constant if all the dimensions are given in cm (in the case of tension, the equivalent water column in cm).

On the basis of the foregoing, the  $pF$  curve can be calculated without measurements, or if there is a measured  $pF$  curve, the characteristics of adhesion and the capillary force can be determined.

To prove the reliability of the procedure some examples are presented on Figure 6 to compare the measured and calculated data. These curves indicate that accuracy required in practice can be attained in this way.

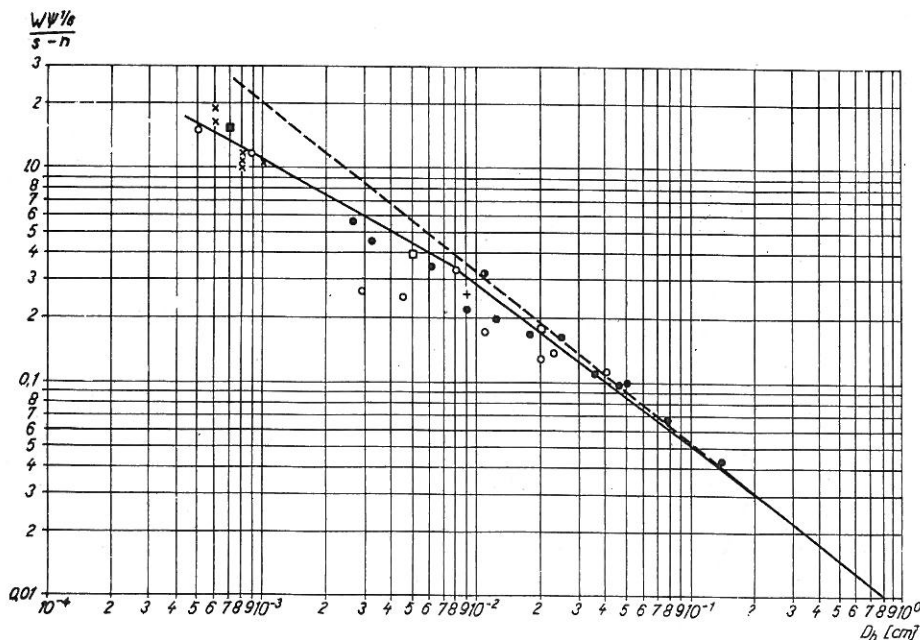


Figure 5

A relationship between the calculated  $\frac{W \varphi^{1/6}}{1 - n}$  value and the effective diameter

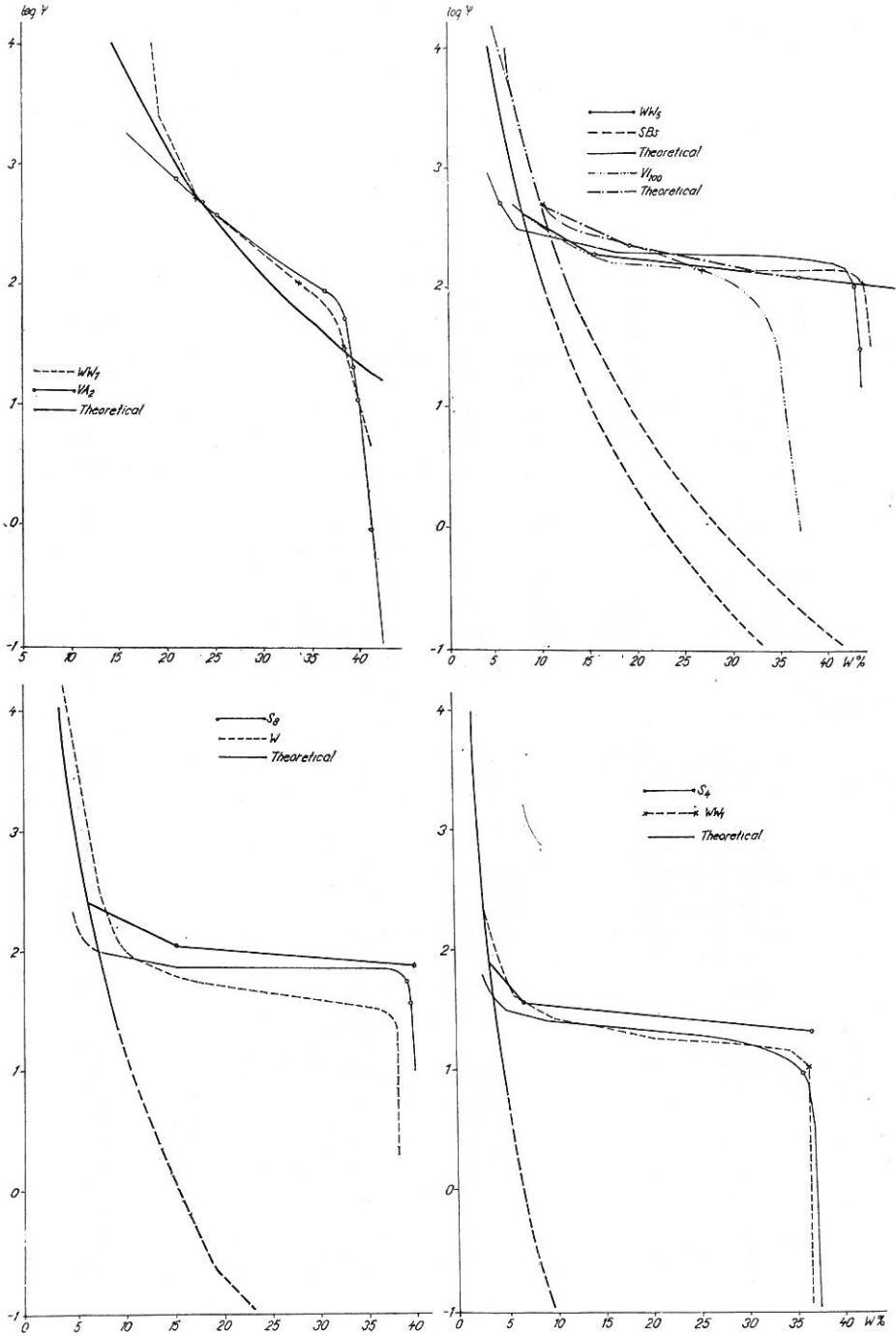


Figure 6 The comparison of calculated and measured pF curves. Sign of sample: see Table 1. Abscissa: moisture in per cent volume

Table 1

Data characterizing the relationship between moisture content and adhesion

Sign of sample	Porosity ( $n$ )	Effective diameter ( $D_h$ )	$\frac{W'p^{1/2}}{1-n}$	According to
$S_1$	0,375	1385	0,044	STAKMAN [10]
$S_2$	0,369	693	0,068	
$S_3$	0,375	500	0,100	
$S_4$	0,375	457	0,100	
$S_5$	0,373	353	0,113	
$S_6$	0,384	250	0,167	
$S_7$	0,396	177	0,170	
$S_8$	0,418	125	0,200	
$S_9$	0,443	89	0,220	
$S_{10}$	0,442	61	0,355	
$S_{11}$	0,425	27	0,570	
$S_{BS}$	0,500	32	0,470	
$WW_1$	0,365	400	0,115	WESSELING and WIT [14]
$WW_2$	0,365	230	0,140	
$WW_3$	0,385	110	0,175	
$WW_4$	0,405	45	0,250	
$WW_5$	0,435	29	0,270	
$WW_6$	0,500	5	1,570	
$WW_7$	0,440	9	1,200	
$WW_8$	0,375	80	0,340	
$WW_9$	0,350	200	0,130	
$VA_1$	0,442	90	0,260	VACHAUD [11, 12]
$VA_2$	0,435	8	1,200	
$VI_{101}$	0,475	200	0,179	VISSER [13]
$VI_{100}$	0,331	50	0,400	
R	0,600	7	1,530	ROSE [9]
W	0,385	110	0,333	WIND [15]
$E_{AP}$	0,465— 0,500	6	1,630— 1,940	ELRICK [2]
$E_{AE1}$	0,445	10	1,080	
$E_{AE2}$	0,480	8	1,160	
$E_{BT1}$	0,390	8	1,030	
$E_{BT2}$	0,390	8	1,070	

### Summary

In the introduction of the study it is determined on the basis of the dynamical investigation of seepage through porous layers that what kind of forces influence the process. Of these forces the molecular ones between grains and water, i.e. capillarity and adhesion have not been studied satisfactorily. The  $pF$  curve, describing the relationship between the moisture content and tension, can be used to determine these forces.

To describe the connection between the  $pF$  curve and the active forces, the complicated network of pores between the grains can be substituted by a bunch of pipes the data of which (diameter and number of pipes) can be calculated on the basis of soil physical characteristics. The summary of this calculation is given in the second part of the study.

The described model renders it possible to refer the theoretical physical correlations determined for the calculation of the forces of capillarity and adhesion to the complicated system of a layer and thus to establish the equation of the  $pF$  curve. On the  $pF$  curve three, sharply differing sections may be distinguished. In the upper part the relationship between the moisture content and tension is determined chiefly by adhesion. The second section, which is approximately horizontal, may be characterized by the height of the capillary zone. In the third section, representing the zone bordering on that of gravitational moisture, the layer is saturated to field capacity, or, if the pore volume is even smaller, completely.

The  $pF$  curves determined by calculations according to the foregoing were compared to measured data. The good agreement found between them proved the applicability of the above described method. Thus it is possible to determine the active forces on the basis of the measured  $pF$  curve, or to draw the  $pF$  curve if the soil physical characteristics are known.

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