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Factors affecting the determination of hydrogen ions, with especial reference to soils

(Faktoren, welche die Bestimmung der Wasserstoff-Ionen
im Boden beeinflussen. — Les éléments influençant la
détermination des ions hydrogènes dans le sol)

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Outline

Introduction. — Review of literature. — Effect of carbon dioxide on soil reaction. — Periodic variation of hydrogen ion concentration. — Effect of drying on the hydrogen ion concentration of soil sample. — Effect of grinding of soil sample on the hydrogen ion concentration. — Soil-water ratio. — Factors affecting the hydrogen electrode determination. — Factors affecting the quinhydrone electrode determination. — Factors affecting the antimony electrode determination. — Colorimetric method: Obtaining the soil extract. Preparation and use of isohydric indicators. — Summary.

Introduction

Probably no phase of soil research has received more widespread attention in recent years than the determination of the hydrogen ion concentration. As a consequence thereof contributions to the literature regarding the methods and particularly their application to soil problems in general have been innumerable and varied. In the determination of the hydrogen ion exponents of soils various factors which affect the determination warrant attention.

It is the purpose of this paper, to discuss those factors affecting the hydrogen ion concentration of soils.

Review of literature

In 1916 Gillespie published hydrogen electrode and colorimetric methods (15) for the determination of the hydrogen ion exponents of soils. The agreement between these results obtained by two different methods was of primary importance. Sharp and Hoagland (34) in a later publication also described an electrometric method for determining the hydrogen ion exponents of soils. With the exception of a few electrometric measurements by Saidel (32) and Fischer (13) little previous work had been done along this line.

Effect of carbon dioxide on soil reaction

At acidities in the neighborhood of pH 5 the effect of carbon dioxide on the hydrogen ion concentration is small but increases with the pH (11). Hoagland and Sharp's (20) results show that the hydrogen ion concentration of acid soil suspensions, in contact with a carbon dioxide content of ten per cent, was little affected. With slightly alkaline soils, however, the hydrogen ion concentration showed a small increase as a result of raising the carbon dioxide partial pressure, while a larger increase was observed with soils containing alkali carbonates. Pierre (29) observed increases in the hydrogen ion concentration of acid and alkaline soils as a result of passing carbon dioxide in from the bottom of the electrode vessel and allowing the soil suspension to become saturated and introducing hydrogen from the top only. The carbon dioxide content used here was obviously much higher than met with in the field. By more closely simulating field conditions it was found that the hydrogen ion concentration of the (water) displaced soil solution was not affected by the slow passage of carbon dioxide through soil in glass percolators for about one-half hour.

The effect of carbon dioxide on the pH values of soils from about pH 4.7 to 8.2 was determined by Biilmann and Jensen (5) with the quinhydrone electrode, using boiled distilled water free from carbon dioxide, aerated distilled water in equilibrium with the normal carbon dioxide pressure of the atmosphere and ordinary distilled water containing 17.2 mg. of carbon dioxide per liter. Their data show that the ordinary distilled water gave with neutral and alkaline soils results about 0.1 to 0.3 of a pH unit lower than obtained with boiled distilled water or aerated distilled water, the latter containing 1.0 mg. of carbon dioxide per liter. With the acid soils the differences between the results with the three kinds of water were negligible. Since the results on all of the soils when using boiled and aerated distilled water were in close agreement, Biilmann and Jensen recommend the use of either boiled or aerated distilled water.

Periodic variation of hydrogen ion concentration

Since there has been observed periodic variations in the hydrogen ion concentration of soils, the time of sampling would appear to be of significance in hydrogen ion concentration studies.

Variations of about 0.7 pH in the surface soils of check plots was observed by Lipman, Prince and Blair (26) from May to November. Results obtained by Kelley (22) show that over a period of a year, monthly tests reveal a fluctuation in the pH value of a soil amounting at times to a pH of 1.0 in the subsoil as well as at the surface. Seasonal variations were also observed in the pH values of soils by Burgess (9). According to Baver (3) the acid soils showed a continual increase in hydrogen ion concentration from May to September, whereas the alkaline soils show no consistent variations. There was a consistent increase in acidity in the case of the acid soils from the spring to the fall with a return to nearly the original acidity the following spring. Acid soils varied as much as 0.9 pH from May to September and alkaline soils about 0.6 pH. The two factors affecting these variations in hydrogen ion concentration of the soil are apparently the rainfall and season.

Effect of drying on the hydrogen ion concentration of soil sample

It has been observed by the writer that air-drying of acid soils slightly increases the hydrogen ion concentration. Burgess (8) observed that air-drying of acid soils had little effect on their hydrogen ion concentration but with slightly alkaline soils the pH values were decreased by air-drying. The variations in pH values of acid and alkaline soils due to air-drying was determined by Rost and Fieger (31). These authors found that some samples became more acid and some more alkaline, with a general tendency, however, for the air-dried samples to become more acid than the fresh ones. From fields on which liming experiments were being conducted the differences observed between fresh and air-dried soils varied from 0.03 to 1.17 pH. Fresh moist soils stored for three months in air-tight glass containers showed a tendency toward increased acidity. The conclusion was drawn that the only reliable indication of field conditions was obtained with freshly taken soil samples.

Healy and Karraker's (19) results show that air-drying acid soils slightly lowered the pH values. Billmann and Jensen's (5) results on soils from about pH 5.2 to 8.3 show the air-dried soils to be slightly more acid than before air-drying. These authors conclude that the air-dried soils show pH values corresponding essentially to the

values found with non-air-dried soils. Results obtained by Joseph and Martin (21) show that oven-drying alkaline soils lowered the pH of the extract as compared with the extract of the undried soil. Under field conditions Kelley (22) found that drying is apparently often accompanied by increased acidity, but not invariably. That the reaction of acid surface soils is not significantly affected by air-drying is shown by the work of Baver (3). With alkaline soils, however, there is a considerable decrease in alkalinity. The air-drying of subsoils caused a marked increase in acidity which increased with depth. For practical purposes, as stated by Baver, it seems that the hydrogen ion concentration of air-dried soils is sufficiently accurate, but fresh samples should be used for refined reaction studies.

The general conclusion seems apparent that drying of soils is as a rule accompanied by a change in reaction, this change in reaction generally being in the direction of increased acidity and with a tendency to be more pronounced with alkaline soils.

Effect of grinding of soil sample on the hydrogen ion concentration

Baver (3) observed that by grinding a soil to pass a 100-mesh sieve the hydrogen ion concentration of the acid samples of Wooster silt loam was little affected. With the alkaline samples, however, the hydrogen ion concentration was increased. It is stated that this was probably due to the exposing of surfaces that had not been affected by the addition of lime. By grinding Brookston and Miami clays, glacial limestone soils, a decrease in acidity was observed. With the exception of one soil Sharp and Hoagland (34) observed that grinding a soil to pass a 200 mesh sieve did not materially change the hydrogen ion concentration of soil suspensions. Out of five acid soils no change was shown by two while three showed a tendency toward a decrease in pH value, in one instance a decrease of 0.3 pH due to grinding. With one alkaline soil, the exception previously mentioned, grinding increased the pH from 6.4 to 7.15. The changes in the hydrogen ion exponent due to grinding are attributable, no doubt, to the solution and hydrolysis of the minerals comprising the soil. For the determination of the hydrogen ion exponents of soils it is preferable, therefore, to use the un-ground sample.

Soil-water ratio

The soil solution, suspension and extract have been employed in the determination of the hydrogen ion exponents of soils, the soil suspension and extract, however, being more generally used.

Some difference of opinion in regard to the effect of the variation of the soil-water ratio on soil reaction is evident in a review of the literature. Sharp and Hoagland (34) by using widely varying proportions of water to soil, found comparatively insignificant changes in the hydrogen exponents. Gillespie and Hurst's (17) results on Caribou and Washburn loams, show an average positive difference for 9 soils of 0.14 pH when the water to soil ratio was varied from 1 to 1, to 2 to 1. The same authors in a subsequent publication (18) show that the differences in exponents caused by varying the water to soil ratio from 1 to 1, to 2 to 1 are distributed like errors about a mean value of $+ 0.04$ pH. There was no apparent correlation between the actual values of the exponent and the differences caused by dilution. Salter and Morgan's results (33) show that the pH value at a soil-water ratio of 1 to 5 varied from 0.10 to 0.85 pH higher than the calculated reaction at a field moisture content of 20 per cent. Results obtained by these authors on acid soils indicated a systematic variation of hydrogen ion concentration with variations in the soil-water ratio, the highest hydrogen ion concentration occurring at high soil-water ratios with a progressive decrease as dilution increased.

Results by Pierre (29) show that variations in the soil-water ratio from 1 to 2, to 1 to 50, cause variations in the hydrogen ion concentration of some soils but not in others. It appears from the data that the most acid soils studied are affected more by changing the soil-water ratio, and this relation seems to hold regardless of the soil texture. Pierre (29) concluded that soils showing a change in hydrogen ion concentration at varying soil-water ratios do not show these changes after the soluble salts and acids are washed out. After washing, the acidity is due to the relatively insoluble acids. It is further shown by Pierre (29) that the soil solution is not at a higher hydrogen ion concentration than the 1 to 2 soil-water suspensions or extract. Several investigators have made a comparison between the hydrogen ion concentration of the displaced soil solution and that of the soil suspension and in general have found the displaced soil solution to have a higher hydrogen ion concentration than the soil suspension. This lack of agreement Pierre attributes to the failure of these investigators to obtain the actual soil solution. Crowther (12) has found a regular increase of about 0.1 pH for a twofold dilution, varying the soil-water ratio from 1 to 1, to 1 to 32. It was concluded by Barnette, Hissink and Van der Spek (2) that the equilibrium with regard to the hydrogen ion concentration between soil and water varies with the soil-water ratio and is dependent on many factors. A more constant hydrogen ion concentration was

shown by the closer soil-water ratios and such ratios should therefore be used for the hydrogen electrode determination.

The writer has preferred for air-dried mineral soils the soil-water ratio of 1 to 2 as being well adapted to the electrometric and colorimetric determinations of the hydrogen ion exponents of soils. For peats or mucks the soil-water ratio may vary from about 1 to 3, to 1 to 7.

Factors affecting the hydrogen electrode determination

In the determination of the hydrogen ion exponents of soils by the hydrogen electrode difficulties have often times been traced to various sources, such as oxidizing agents, unsaturated substances, insufficient supply of hydrogen, nitrates, "poisoned" electrodes etc.

It has been observed that if the electrode vessel is not shaken during the measurement the potential sometimes increases so rapidly that any measurement would be a forced one, and readings made after the potential apparently became constant would in general be in error. Gillespie and Hurst (18) attributed this to the presence of nitrates and possibly other oxidizing agents. With the shaking type of pyrex electrode vessel with a volume of about 70 cc. (Figure 1) used by the writer (35) equilibrium is generally obtained in 5 to 10 minutes, the readings being made during agitation. Any errors due to bubbling hydrogen through the suspension or by making contact with the standard electrode within the suspension are eliminated, as the atmosphere above the suspension is swept out with pure hydrogen (but not bubbled through the suspension) and contact with the standard cell is drawn into the end B (Figure 1) of the vessel thus avoiding any possible contamination of the soil suspension with potassium chloride solution.

Considering the effects of oxidizing agents such as nitrates, Joseph and Martin (21) observed that by slowly passing hydrogen for 5 hours through a neutral 1 per cent solution of sodium nitrate in the presence of a few square centimeters of platinized platinum foil the pH rose to over 10 and gave a heavy precipitate with Nessler's reagent. It was concluded by these investigators that no disturbing effect is likely to be introduced by nitrates up to 500 p.p.m. of soil. Sharp and Hoagland (34) state that while with extracts of acid soils the reduction of nitrates precludes the use of the hydrogen electrode it is not believed that appreciable errors would be caused in the case of nutrient solution containing nitrates. Gillespie and Hurst (18) stated that the hydrogen ion concentration of the extract comparatively free from soil particles was meaningless and indefinite, this being attributed to the presence of nitrates in a solution weak in buffer action.

In regard to poisoned electrodes a sample of soil submitted to the writer gave with the hydrogen electrode a negative potential and a correspondingly absurd pH value. The container in which the soil had been transmitted was labeled "Bichloride of Mercury". Fifteen grams of a similar sandy soil were treated with 10 mg. of HgCl_2 and an effect

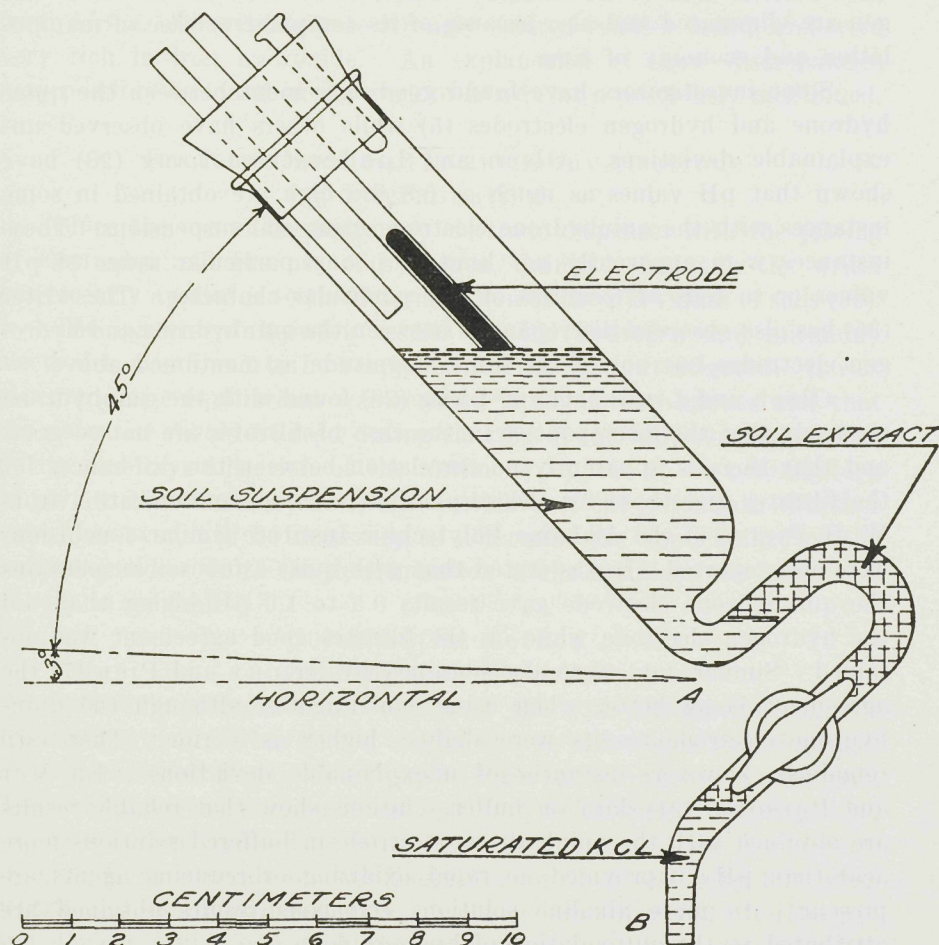


Figure 1.

greater than that mentioned above was observed. This was apparently an instance of electrode poisoning as a result of the soil being contaminated with HgCl_2 from the unclean container. With other soils higher in organic matter the effect was comparatively small. A second sample of the original soil, but free from HgCl_2 , was found to have a pH value of 5.3.

Factors affecting the quinhydrone electrode.
determination

Since the development of the quinhydrone electrode and its adaptation to soils by Biilmann (4) it has been rather extensively employed in view of the fact that coating of the electrode and the use of hydrogen are eliminated and also because of its comparative ease of manipulation and economy of time.

Some investigators have found good agreement between the quinhydrone and hydrogen electrodes (5) while others have observed unexplainable deviations. Olsen and Linderstrøm-Lang (28) have shown that pH values as much as 0.8 too high are obtained in some instances with the quinhydrone electrode using soil suspensions. These instances were apparently not limited to any particular range of pH values or to soils or localities of any particular character. The writer (35) has also observed discrepancies between the quinhydrone and hydrogen electrodes but not of the same magnitude as mentioned above.

Olsen and Linderstrøm-Lang (28) found with the quinhydrone electrode that the discrepancies in the case of filtrates are not so great and that there is apparently no correlation between the differences for the filtrates and those for the suspensions. In a communication from W. H. Pierre of the Alabama Polytechnic Institute similar conclusions were also reported. It was stated that with quite a few soil suspensions the quinhydrone electrode gave results 0.5 to 1.0 pH higher than did the hydrogen electrode while on the filtrates good agreement was obtained. Similar data were also obtained by Brioux and Pien (7) the agreement being better when using centrifugates, although the quinhydrone electrode results were slightly higher as a rule. There still remained, however, instances of unexplainable deviations. La Mer and Parsons' (24) data on buffer solutions show that reliable results are obtained with the quinhydrone electrode in buffered solutions more acid than pH 8.0 provided no rapid oxidizing or reducing agents are present. In more alkaline solutions erroneous results obtained are attributed to the autoxidation of hydroquinone.

The writer has recently been advised by one investigator that by the use of gold electrodes in place of platinum no trouble had been experienced on several hundred soils using the quinhydrone electrode method. This should not be construed, however, as a recommendation for the elimination of discrepancies in all cases. It is stated by Lindeman (25) that quinhydrone electrode results are not reliable in liquids containing iron in the form of ions or even as hydroxide. A series of determinations with the quinhydrone electrode in colloidal solutions of iron hydroxide

gave results wholly different from the actual values. Various sources of errors in the use of the quinhydrone electrode have been discussed in a valuable contribution by Biilmann and Jensen (5). Christensen and Jensen (10) have observed unusual discrepancies between the quinhydrone and hydrogen electrode results on certain laterite soils from Africa. These soils were strongly colored reddish brown and were very rich in iron hydroxide. An explanation of these discrepancies may possibly be found in the work of Lindeman previously mentioned.

Factors affecting the antimony electrode determination

Since the use of the antimony electrode dispenses with the plating of electrodes and the use of hydrogen, quinhydrone, etc., the writer has recently applied it to the determination of the pH values of soils (36).

The agreement between results by the hydrogen and antimony electrodes was found to be very good for the soils investigated. It was observed that equilibrium was reached in about one minute and that the potential should be read during shaking of the soil suspension. The purity and crystallization of the antimony appear to be contributory in part to the constancy and reproducibility of the potentials. Further work, however, will be necessary to determine the applicability of the antimony electrode to the determination of the hydrogen ion exponents of soils in general.

Colorimetric method

Obtaining the soil extract

Different procedures for obtaining the soil extract used in the colorimetric method have been employed. In this regard mention may be made of centrifuging, filter paper, Pasteur-Chamberland filters, flocculating agents, suction filters and dialysis through collodion sacks.

Pierre (29) states that centrifuged soil extracts show an increase of 0.25 pH as a result of centrifuging in an open test tube but when centrifuged in a closed test tube no change was observed. Gillespie and Hurst (18) found that the colorimetric and hydrogen electrode results on a large number of soils agreed within the experimental error. The extract was centrifuged in an open test tube using a closed centrifuge. These same authors found that soil extracts (18) filtered through filter paper were incorrect and variable depending on the paper and its treatment. Barnette, Hissink and Van der Spek (2) observed that the filtrates of the soils investigated were acid but always less acid than the suspensions. It was concluded by Atkins (1) that the pH values of some soil extracts are markedly modified by filtration even after

the rejection of a first filtrate. Nehring (27) states that the use of filtrates should be avoided, however, if filter paper must be used, only quantitative filter paper having been repeatedly washed with boiled distilled water should be employed. Results by the writer with Pasteur-Chamberland filters show an increase in acidity with four alkaline soils as a result of filtering. These results are in agreement with those of Fisher (14).

Colloidal iron has been used by Gillespie (16) for the clarification of soil extracts but this author did not feel justified in recommending its use on the basis that other soils with little buffer action might be affected by the residual acidity of the colloidal iron. A special grade of barium sulphate was used by Kühn as a clarifying agent, the limit of accuracy being 0.5 pH. Pierre and Parker (30) used a modified suction apparatus devised by Truog (37) and found good agreement between the colorimetric results on these filtered extracts, collodion sack extracts and the electrometric results. They washed the filter paper 10 to 15 times with hot conductivity water, dried it at 50° and stored in a dessicator.

Preparation and use of isohydric indicators

When dealing with lightly buffered soil extracts the acidity of the indicator solution may be such that it may change that of the unknown. In an article by Birge and Acree (6) it is stated that by titrating the solutions of the monobasic salts of the sulfonphthalein indicators with more alkali and so adjusting the indicator solutions to any desired pH it is possible to mix the indicator with a solution of approximately the same pH value and prevent any appreciable change of the pH when the solution has weak buffer properties. The procedure of either having the indicator and unknown solution isohydric or of bringing the indicators to their half transformation points is important when dealing with very weakly buffered solutions, however, most soil extracts are sufficiently well buffered so as not to be affected by the indicators prepared as described by Clark (11). For very precise work the isohydric method may be preferable.

The isohydric indicator method is the use of an indicator solution made up to the same pH as the unknown in order to prevent the unknown and the indicator from changing each other and to give a final color-buffer mixture (unknown or standard plus indicator) at the same pH as the unknown (or standard if used). Procedures devised by Miss Fawcett of the U. S. Department of Agriculture and S. F. Acree of the U. S. Bureau of Standards for the preparation and use of isohydric

indicators are as follows: Stock indicator solutions are made up as M/1000 or 0.02 per cent or any desired concentration of the monobasic salt or brought to the first faint color change with N/10 NaOH or HCl; 50 or 100 cc. portions are put into individual pyrex flasks and adjusted as follows. As an example take bromthymol blue covering the pH range 6.0 to 7.6. Put in a clean pyrex test tube 0.2 cc. or less (even 0.05 cc.) of a pH 6.0 buffer solution and 0.2 cc. of the indicator solution and stopper the test tube which is then laid on its side as the buffer color standard. Then 0.2 cc. of the indicator is put into another clean pyrex test tube of the same bore, and stoppered and laid beside the other test tube whereby the colors are compared. If the pH of the indicator solution is below or above the pH 6.0 buffer-color standard it is adjusted by cautiously adding small volumes of N/10 NaOH or HCl until the color of 0.2 cc. just matches the buffer color standard. The next stock of pH 6.2 indicator is similarly prepared by comparison with a pH 6.2 buffer-color standard. In this way the ranges of the different indicators may be covered in steps of 0.2 pH. Of course some samples of the indicators are impure and these solutions do not always keep indefinitely but restandardization can easily and quickly be made. As a rule the change in pH of these stock solutions between use and occasional restandardization is small.

The isohydric indicators are used as follows: Add to 10 cc. or other desired volume of the unknown 0.2 cc. or other necessary volume of the various indicators adjusted to their midpoints and determine the approximate pH by comparison against the usual buffer-color standards or the drop-ratio standards of Gillespie. The buffer color standards are prepared by adding to 10 cc. of the buffers, 0.2 cc. of the corresponding isohydric indicator. If the approximate pH of the unknown is below the indicator midpoint then to a second sample of the unknown add the next isohydric indicator lower than the approximately determined pH. If the approximate pH is above the indicator midpoint add the next isohydric indicator higher than the approximately determined pH. If the unknown is well buffered these two tests will give practically the same pH. If the unknown is well buffered the two tests will give practically the same pH. If the unknown is weakly buffered the two tests may vary 0.1 to 0.2 pH depending on the buffer capacity of the unknown and the divergence of its pH from that of the midpoint indicator and a third test may be necessary. If the pH of the second test was farther from the indicator midpoint than the isohydric indicator used in the second test, then the indicator for the third test is the next one farthest from the midpoint. If the pH of the

second test was nearer the indicator midpoint than the isohydric indicator used in the second test then the indicator for the third test is the next one nearest the indicator midpoint. This quickly gives two "unknown-color mixtures" whose pH values are between those of the two indicators used therein and it is easy by comparison with the color standards to judge the correct pH of the unknown. Data have also been obtained which take into account the salt errors involved in the use of the buffer standards.

Summary

The various factors affecting the hydrogen ion concentration of soils such as carbon dioxide, periodic variation, drying and grinding of soil samples and the variation of the soil-water ratio are discussed.

Different factors affecting the hydrogen, quinhydrone, and antimony electrode results and the colorimetric results such as methods of obtaining the soil extract and the preparation and use of isohydric indicators are discussed.

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Some contributions to the knowledge of capillary phenomena in connection with the heterogeneity of the soil

(Bijdrage tot de kennis van capillaire verschijnselen in verband met de heterogeniteit van den grond. — Beiträge zur Kenntnis der Kapillarerscheinungen im Zusammenhang mit der Heterogenität des Bodens)

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Introduction. — The water in the soil in connection with capillary actions. Investigations of others regarding capillary heights of rising and conclusions drawn therefrom. — The capillarimeters and their manner of acting. — Results of the investigation. Influence of the thickness of the layer of soil. Minimum and maximum capillarity pressure. — The water content in and above the capillary zone. Sejunction water. Funicular working. — The relation between the size of the soil particles and the negative capillarity pressure. — Concluding remarks on capillary action in connection with the heterogeneity of the soil and the presence of cavities and canals. — Summary. — Literature.

Introduction

The growth of crops is to a very great extent influenced by the proportions of water and air in the soil.

The water content depends on the state in which the water is found, and this state is dependent on the size and shape of the pore-spaces.

These spaces may be divided into capillary and non-capillary spaces. This means roughly a division of the soil into particles > 2 mm. and < 2 mm. Wollny (1) found, with a grain-size of from 1 to 2 mm. a capillary rise of from 5 to 9 mm. Von Klenze (2) observed that, with a grain-size of 2.5 mm., no further capillary rise took place.

Soils suitable for cultivation consist largely of particles < 2 mm., and even if they contain a comparatively high content of larger particles without becoming unsuitable for cultivation, this must be ascribed to the fact that the larger particles are distributed among the smaller ones in such a way that they have no adverse influence on the state in which the water may be present.

The capillary spaces may intersect the soil as a cellular system of small channels, in which no non-capillary spaces occur. Such a condition will be found below a certain depth, where weather-conditions and physiological processes have no more effect; here the granular structure is found. Closer to the surface the cellular system of capillaries is interspersed with non-capillary spaces. In the topmost layer these

non-capillary spaces are of such frequent occurrence that we can no longer speak of one capillary cell-system; instead of this we find a large number of small ones. The structure is in this case a crumb-structure, or even a clod-structure. The layers between the depths with a perfect granular structure and those with a crumb-structure show every kind of transition. The non-capillary spaces which occur here do not, as a general rule, render impossible the continued existence of the inter-connection of the capillary cell-system.

The writer divides the non-capillary spaces into cavities and canals. The cavities are connected with the atmosphere only by capillary spaces, whereas this connection takes place, in the case of the passages, both directly and by means of capillary spaces.

When water is present in the soil, liquid films occur in the capillary spaces, causing a negative capillarity-pressure. The water-mass in the capillary cell-system, which is under the influence of this negative capillarity-pressure, is determined by the magnitude of this pressure.

As the soil-particles vary greatly, this is also the case with the capillary spaces. This heterogeneous composition or heterogeneity of the soil gives rise to phenomena which make the condition and quantity of water in the soil quite different from what it would be if all the soil-particles were of the same size. The object of the present monograph is to contribute to the knowledge of these phenomena.

Chapter I

The water in the soil in connection with capillary actions. Investigations of others regarding capillary heights of rising and conclusions drawn therefrom

The negative capillarity-pressure

The water in the soil is in contact with the air on the one hand and with the soil-particles on the other. The area of contact with the air is termed the free surface and that with the solid matter the contact surface.

On the free surface we have, besides the atmospheric pressure, the cohesion-pressure, the size of which depends upon the shape of the surface. With a concave surface the cohesion-pressure is smaller and with a convex surface larger than with a flat surface. This increase or, as the case may be, decrease, of the cohesion-pressure is termed the capillarity-pressure, and may be represented as follows:

$$D_{\text{cap.}} = \frac{H}{2} \cos \delta \left(\frac{1}{R_1} + \frac{1}{R_2} \right).$$

H is a constant and means the surface tension per unit of surface of a sphere with a radius of one. $\frac{H}{2} = \sigma$ is the capillarity-constant or cohesion-constant (according to Quincke). The capillarity-pressure may therefore also be represented as follows:

$$D_{\text{cap.}} = \sigma \cos \delta \left(\frac{1}{R_1} + \frac{1}{R_2} \right).$$

R_1 and R_2 are the smallest and largest radius of the curved surface, δ is the tangential angle, and $\cos \delta = \frac{\beta}{\sigma}$, in which β is the adhesion-constant (3).

In the case of liquid rings, such as occur between soil-particles, the centres of the curves lie outside the liquid, and we have a negative capillarity-pressure.

If the capillary cell-system in the soil is regarded as a sequence of very short cylindrical tubes, then the radius R of the tubes is also radius of curvature, and may also be written

$$D_{\text{cap.}} = \frac{2 \sigma \cos \delta}{R}$$

β can never be greater than σ , at the most equal to it. In the latter case $\cos \delta = 1$, which is the case with complete moistening. Then

$$D_{\text{cap.}} = \frac{2 \sigma}{R}$$

Without complete moistening e. g., when the soil is dry, the radius of curvature R' is greater than the radius of the capillary space and

$$R' = \frac{R}{\cos \delta}$$

With dry soil $D_{\text{cap.}}$ will therefore be smaller.

The negative capillarity-pressure causes movement. When equilibrium is reached, the gravitation is equal to the capillarity-pressure. If capillary rising takes place, then the theoretical height of rising $h = D_{\text{cap.}}$ (expressed in cm. water-pressure).

If the length of a soil-column in which the capillary rise occurs, is less than the capillary height of rising, then the menisci on the surface of the ground are flattened down, and the radii of curvature will be greater than the radius of the capillaries.

The water content in the capillary zone

The plane in the soil where the hydrostatic pressure is equal to that of the atmosphere, is called by Versluys the phreatic surface (4).

Up to a certain height above the phreatic surface the soil is still saturated with water, so that — as Versluys says — “the water content of sand in the capillary zone agrees with the porosity figure” (5). The particular structure, however, of the topmost layer of the soil, which — as already remarked in the Introduction — is the result of biological processes and weather influences, will cause the content of water in the capillary zone there to be lower than Versluys gives¹). The presence of canals in the top-soil is at the same time a guarantee that the roots of the crops have sufficient air for their development. It may be assumed with Versluys that “most land-plants with their roots remain in that part where there is still air”, but not that this must therefore be “above the capillary level” (6).

Funicular action

Above the capillary surface the spaces are only partially filled with water, which is also held fast by capillary forces. According to Versluys (7), the capillary water is followed first by funicular water, and this again by pendular water. According to this writer, when water has been withdrawn from the funicular zone, it will be replaced by water from all sides, and thus also from the capillary zone. Such a replacement must be assumed in consequence of an experiment by Versluys (8). The writer believes, however, that he has demonstrated by an experiment of his own (Chapter IV) that the funicular movement is so slow and that so little water is brought up, that it has no effect on the supply of water to the plants.

Capillary rise in the capillary zone

Capillary ascent only takes place if the required difference of pressure is present. Thus in a tube of soil, which is placed in water, a capillary rise will be observed, owing to the fact that the atmospheric pressure plus the cohesion-pressure work on the free water-surface outside the tube, and a pressure, smaller by the amount of the capillarity-pressure on the concave liquid tables at the same height in the tube.

If over a large area of soil of homogeneous constitution the same amount of water is with-drawn from every part of the capillary zone, there will be no capillary rise, unless at the same time the necessary difference in pressure arises. This difference in pressure will i. a. arise when the sections of canals form part of the phreatic surface; out of the free liquid tables in these canals, after water has been withdrawn from the capillary zone, water can rise by capillary attraction.

¹) Chapter VI.

In this connection it is desirable from an agricultural point of view to make a distinction between a free phreatic surface and an enclosed phreatic surface. Capillary rising will take place from out of a free phreatic surface, if water is withdrawn from the capillary zone. If, on the other hand, the phreatic surface is completely enclosed, then the fall of the capillary surface will result in an equally great fall of the phreatic surface.

It is in canals and cracks in the soil that a free phreatic surface can occur, whilst further the surface of the water in ditches, canals and rivers also acts as such.

It is plain that water will be able to flow from a higher lying phreatic surface, even if it is enclosed, to a lower-lying one; a rise of this latter entails a rise of the capillary surface, in which case also we may speak of a capillary rise.

Van Maanen (9) argues that, after water has been withdrawn from one of several capillary tubes, a "rise takes place in that one tube, but a fall of the water-level as a whole." He says further: "It is evident that there can be no question of a rise of water, let us say, out of the subsoil. Where should it come from, unless a vacuum were to arise below or water were to come from the side. We may therefore say that capillary rise does not take place."

There is a contradiction in this argument, in which we are first told that a rise takes place, and then that it does not. Moreover, the conclusion that no capillary rise takes place is too absolute. Van Maanen goes here to the opposite extreme from the opinion of others, which is dealt with in the following paragraph.

Capillary rise in dry and moist soils

The observation of capillary rise in the laboratory has certainly contributed to the view that capillary rise takes place as a rule in nature, and that it is of the greatest importance in the supplying of water to the plants (10, 11, 12, 13, 14, 15).

As a rule capillary rise is determined in the following way:

Tubes are filled with dry soil, during which process they are continually softly tapped. The extreme ends of these tubes, provided with a small cloth, are then placed or hung in water. Observations are then made as to the times in which the water rises to a particular height, or how high the water has risen in a given time. Just as in the determination of the volume-weight of the soil, this tapping must be continued so long that no further diminution in volume takes place. According to Wahnschaffe and Schucht (16) this period is from $\frac{1}{2}$ to 1 hour,

according to Heinrich (17) this manner of filling gives, in the case of soils with a low humus content practically the same results as pouring the soil into the tube with water.

The largest rises noted which are to be found in literature, justify the supposition that the manner in which they have been determined is the cause of too low results. Mitscherlich (18), for instance, was unable to find, in three months' time, a greater rise than 0.8 M. in tubes filled with dry soil. Tulaikow (19) found in 513 days with fine-textured soils a maximum rise of 1.35 M. The greatest rise found by Wollny (20) was about 1 M. (for granular loam, 0—0.25 mm.); in Wollny's tests the maximum rise for finer soils was not found, the observations being of too short a duration. Loughridge (21) never observed in 200 days (not even with heavy soils) a greater rise than 1.27 M. In the case of dry soils the cosine of the tangential angle is smaller than one and the negative capillarity pressure will be smaller. If on the other hand there is a thin layer of water on the soil particles, this may bring about a considerable increase of the negative capillarity pressure, and so of the rise.

If however the test is continued for a long time, the capillary rise, owing to the condensation of water vapour on the dry soil particles, will reach the same height as in previously wetted soil. Hilgard (22), who is inclined to this opinion, says "Capillary movement takes place in moist soils more rapidly than in dry ones, although when sufficient time is given the final adjustment will be the same."

With dry soils with a very high content of fine particles a movement is however found after a very long time, which is considerably smaller than the actual one. The continuously decreasing and even at first very slight rapidity of movement, whereby the capillary supply finally becomes as great as the evaporation, will play a part here. Moreover, the great specific surface will demand more water for complete moistening.

It may be assumed with a very fair degree of certainty that in dry, coarse-textured soils the rise observed after a very long time will differ little from the real one. The writer found with a tube filled with dry sea-sand in 150 days a capillary height of rising of 61 cm. By determining the negative capillarity pressure in the way described in Chapter II, 63 cm. was found.

In Chapter IV, p. 24, a cause of the smaller movement is indicated.

It is strange to find a case reported, in which the total movement (and also the rapidity of movement) in the case of damp soil is smaller than in dry ground. Krawkow (23) reports that in dry sand the water rose to 84.2 cm. and in the same sand with water-contents of 0.51 to 2.39 % about 40 cm.

Krawkow does not say whether the movements in the damp soil were clearly perceptible. Moreover, the distribution of the water in the damp soil may well have been such that no further displacement of air was possible so that the water was prevented from rising higher.

Significance of the velocity of capillary movement

Great importance is often attached to the velocity of capillary movement. Thus Wollny (24) says that he paid particular attention to this in his experiments, as "dieselbe für die Durchfeuchtung des Bodens hauptsächlich von Belang ist."

As the movement increases, the velocity decreases, owing to the continual increase in the size of the friction-surface and the increasing weight of the rising column of water. For the same reason the water in fine-textured ground will at first rise more slowly than in a coarse-textured one. The diminution in velocity in the fine-textured soil is however relatively smaller, and in consequence the velocity may be greater in the fine-textured soil at a particular height than in the coarse-textured one. Below this height the water will rise more rapidly than in the coarse-textured soil.

The above must be carefully borne in mind when soils are indicated in literature, in which the capillary movement of the water is the quickest. Briggs and Lapham call attention to this, too, in this sentence (25): "It is therefore important to know the rate at which water can be furnished through capillary action for a soil column of any length up to the limiting value; for, while a soil may be capable of maintaining capillary action through a long column, the rate of translocation may be so small as to be of little practical value."

Wollny (26) mentions a law which is important for the movement of water: „Die Boden-Kapillarräume von einer bestimmten Größe (wahrscheinlich die von 0.05 und 0.10 mm.) leiten das Wasser am schnellsten.“ Atterberg (27) found for the fraction 0.05—1 mm. a maximum rise of 1.055 M.

Wollny's law, here quoted, can only become of importance, if capillary supply is possible, and this possibility only becomes a reality in nature when a free phreatic surface of a fair extent occurs at such a depth that the plants can profit by a capillary supply.

A pronouncement of Atterberg's (28) may be quoted here, from which it is evident that he attaches great importance to capillary movement, with no mention of the possibility of such movement: "The movement in 24 and 48 hours respectively is of great importance to the plants. In dry periods it is the subsoil which has to provide the plants with water.

The evaporation from the surface of the soil and from the plants is most vigorous during the day. During the night the subsoil has to bring up fresh quantities of water from the subsoil to the surface of the soil."

Determination of the capillary rise in other ways

Versluys (29) determines the capillary rise in quite a different way from the usual one. By means of a capillarimeter, in which the soil to be tested is put on to a bed of coarse sand, he observes how high mercury is drawn up in a narrow tube by the negative capillary-pressure and finds

$$s = 12.6 h + a,$$

s being the capillary rise, h the height through which the mercury has risen, and a the total thickness of the soil in the capillarimeter.

Versluys also determines the capillary rise by exposing the capillarimeter to evaporation. As soon as the mercury begins to fall, the rise s is calculated from the rise h_1 of the mercury:

$$s = 12.6 h_1 + b,$$

b being the thickness of the soil - bed on which the soil to be tested is laid.

Versluys thus determines the capillary rise in two ways, and evidently gets the same results. This point is again referred to in Chapter III.

The rise was determined by Gardner (30) by a similar method to that of Versluys. The arrangement of the "capillary potentiometer" of Gardner differs somewhat from the capillarimeter of Versluys, but the procedure is based on the same principle.

Briggs and Lapham (31) determined the capillary rise by ascertaining at what height a column of soil, where the water at the surface was exposed to an equable evaporation, was still able to adjust the evaporating water by capillary action.

Chapter II

The capillarimeters used and their manner of acting

The negative capillarity-pressure was determined by the writer in various ways with capillarimeters as shown in figs. 1, 1a, 2, 2a, 3, 3a, 4 and 4a; figs. 1 and 1a represent the same capillarimeter, as is also the case with figs. 2 and 2a etc. In the tests with the apparatus in figs. 2, 2a, 3, 3a, 4 and 4a sub-pressure was used; these capillarimeters were especially used when a great negative capillarity-pressure was to be expected.

The capillarimeter in fig. 1 consists of 2 cylindrical glass tubes. A piece of linen is tied round the end of one of the tubes with a thread, care being taken that the rag is well-stretched. The other tube is put

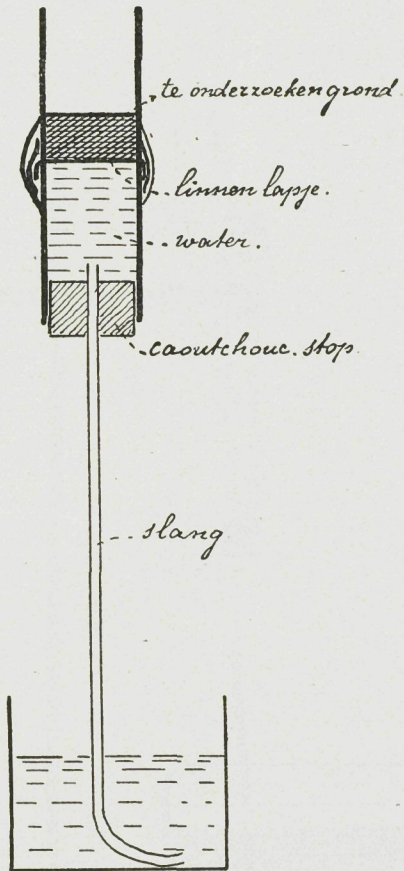


Fig. 1.

Translation of the Dutch letterpresses:

te onderzoeken grond = soil to be tested

linnen lapje = pice of linen

water = water

slang = rubber tube

on to this, and the connection of the two tubes achieved by putting a rubber band, previously treated with an adhesive, round them. In order to be sure of an air-tight joint, the rubber is smeared with melted

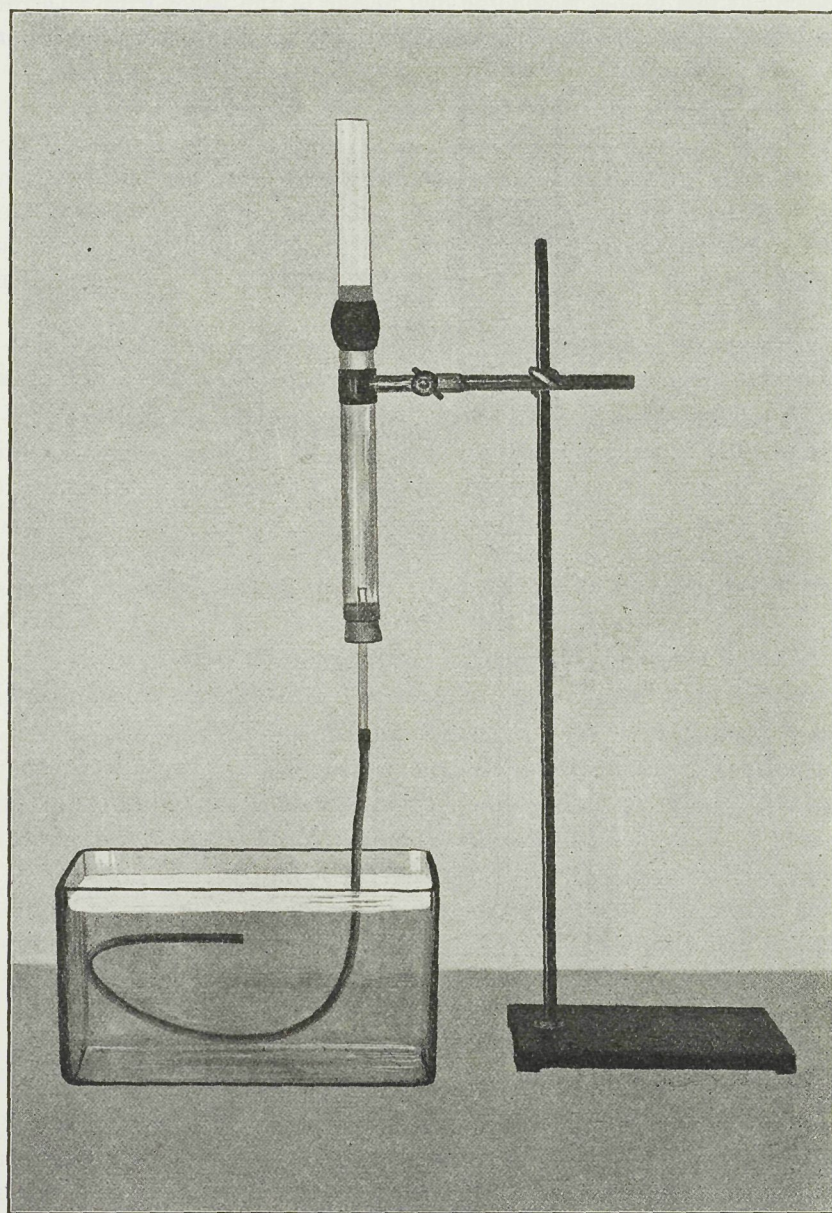


fig. 1a.

sealing-wax, to which a dash of methylated aethylalcohol has been added. A rubber stopper, with a hole bored through it, closes the end of the two connected tubes. From one tube, passed through the stopper, hangs a rubber tube into a vessel of water.

The apparatus is so far filled with water that this is just above the linen rag: care is taken that there is no air under the rag. The soil for

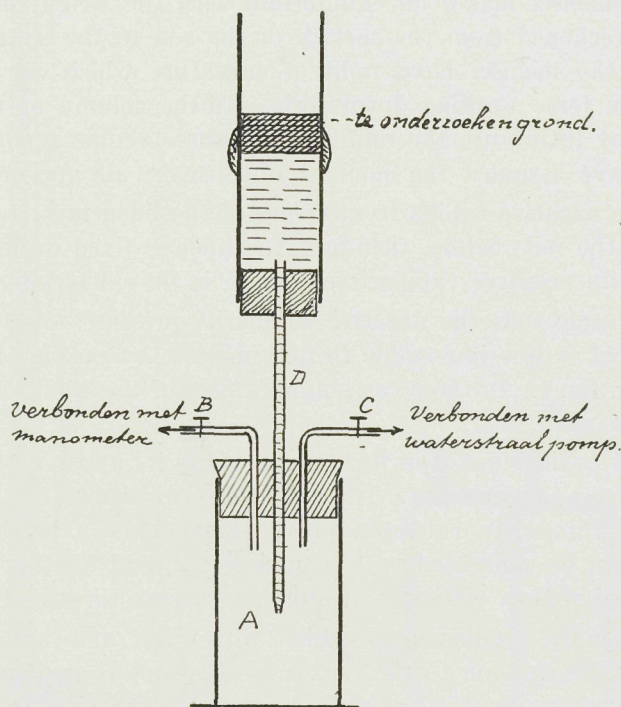


Fig. 2.

Translation of the Dutch letterpresses:

te onderzoeken grond = soil to be tested:

verbonden met manometer = connected with manometer

verbonden met waterstraalpompe = connected with water-jet airpump

which the capillary rise is to be determined, is mixed with water to a pasty mass, so that the soil particles, after being brought on to the rag, will sink in as thin a layer of water as possible. After the soil has been put in, the apparatus is lifted up a little and the lowest part of the glass tube is put into a clamp; the distance from the piece of linen to the water-table in the vessel may be altered by moving the clamp.

Beginning with a small distance, this is increased at intervals. Finally air appears under the rag, whilst the water sinks. The distance now measured in cm. is the negative capillarity-pressure in cm. water pressure¹⁾.

When the water is no longer above the soil-layer and the surface of the soil has become dry, the negative capillarity-pressure of the hollow menisci makes an equilibrium with the weight of a column of water, reckoned from the surface of the soil to the water-table in the vessel; the menisci have radii of curvature which are in agreement with the force working downwards. If the column of water is made longer by lifting up, the radii of curvature become smaller, and, when these have assumed the smallest dimensions, air appears.

The negative capillarity-pressure of the linen must be smaller than that of the soil; before, therefore, the linen is fixed on in the way described, its negative capillarity-pressure is first determined²⁾.

In some soils the negative capillarity-pressure was found to be so great that it was impossible to determine it by means of the capillarity-meter in fig. 1. In these cases apparatuses of the kind shown in fig. 2, 3 and 4 were used.

The capillarity-meter in fig. 2 is, so far as its upper part is concerned, the same as that in fig. 1. The glass tube D is drawn out to a point and projects through a rubber-stopper, which closes a bottle A. A tube which can be connected with a manometer, and another which can be connected with a water-jet airpump, also pass through the stopper.

When the capillarity-meter is filled with water, and the soil to be tested has been brought on to the rag, it is necessary to wait until the water standing above the soil has soaked through. The apparatus is connected with the manometer and the water-jet airpump. The tap B in the pipe connecting with the manometer is open, and the tap C in the pipe connecting with the water-jet airpump is at first closed. The pump is started and by carefully opening a tap C a slowly increasing subpressure can be obtained in the bottle A, which can be read off on the mercury-manometer. Meanwhile water drips out of D into the bottle A. C is occasionally closed again, and it is necessary to wait until the dropping ceases; equilibrium is then reached. Finally air appears under the rag, and at once the dropping rapidly increases or the water spurts out of the glass tube; moreover, the mercury falls in one limb of the manometer

¹⁾ The negative capillarity-pressure will hereafter always be expressed in cm., by which is meant cm. water-pressure prevailing in the soil-layer.

²⁾ The neg. cap. pr. of the linen used varied from 16 to 25 cm.

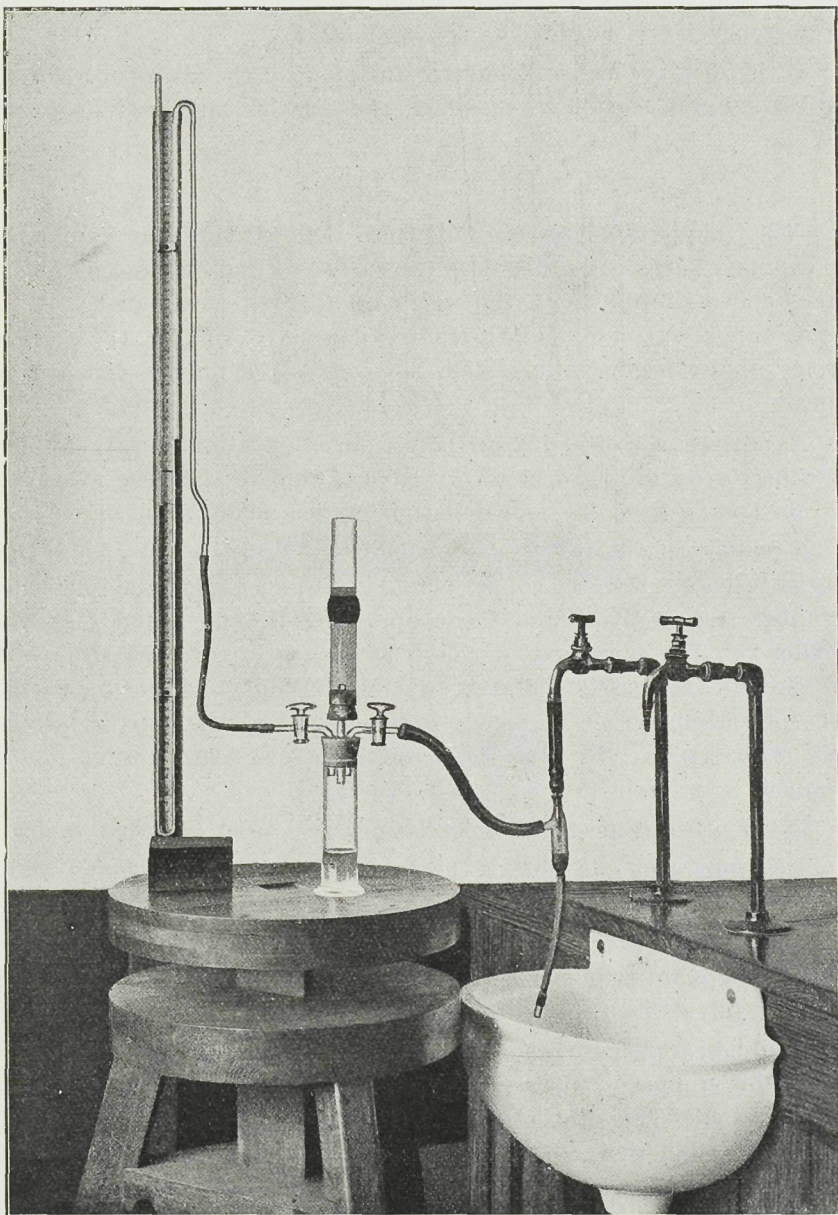


fig. 2a.

and rises in the other; besides which a sucking of air is audible at that moment. As soon as air appears under the linen, the distance between the mercury levels is immediately read off.

If the distance from the linen to the point of the glass tube is h cm. and the subpressure is n cm. mercury, the negative capillarity pressure is

$$(h + 13.6 n) \text{ cm.}$$

What happens here is the following: Before subpressure is induced, the capillary surface is situated on the surface of the soil, and its tension makes an equilibrium with the weight of the water-column h . By inducing subpressure we make the radii of curvature smaller, the capillary surface finally begins falling, and, as soon as the linen is reached, air appears.

As after much use the air-tight connection of the two cylindrical tubes may cease to be so, it is advisable to replace the linen every now and then by a new one, a capillarimeter was made as in fig. 3.

A rubber ring A fits into a copper ring R with a flat edge. On a ledge in A lies a perforated copper plate P, to which a linen rag is attached. A rubber ring D fits round the copper ring R, and round D a glass cylinder C. The cylinder C is closed by means of a rubber stopper K, and through this passes the glass tube M. A copper plate R_2 , provided with some copper rods S, with a screw-thread at the top, is fastened down with screws. By tightening up the screws the air-tight joint is obtained.

In all other respects this capillarimeter is used like that in fig. 2.

The apparatus can quickly be taken to pieces for cleaning and if necessary for replacing its parts.

The capillarimeter in fig. 4 was also used in the experiments. When only a small quantity of soil is available for the test, so that it is necessary to be careful with it, this apparatus has special advantages.

A rubber stopper B with a hole in it is placed into a copper cylinder A, and on this stopper is laid a perforated copper plate on which a piece of linen is fixed. The rubber stopper C is then pushed into the casing. Two glass cylinders D and E are put in above and below. A rubber stopper H, through which a glass tube L projects, fits into E.

The parts can quickly be put together and taken apart.

Experiments are conducted with this apparatus as with the two capillarimeters above mentioned.

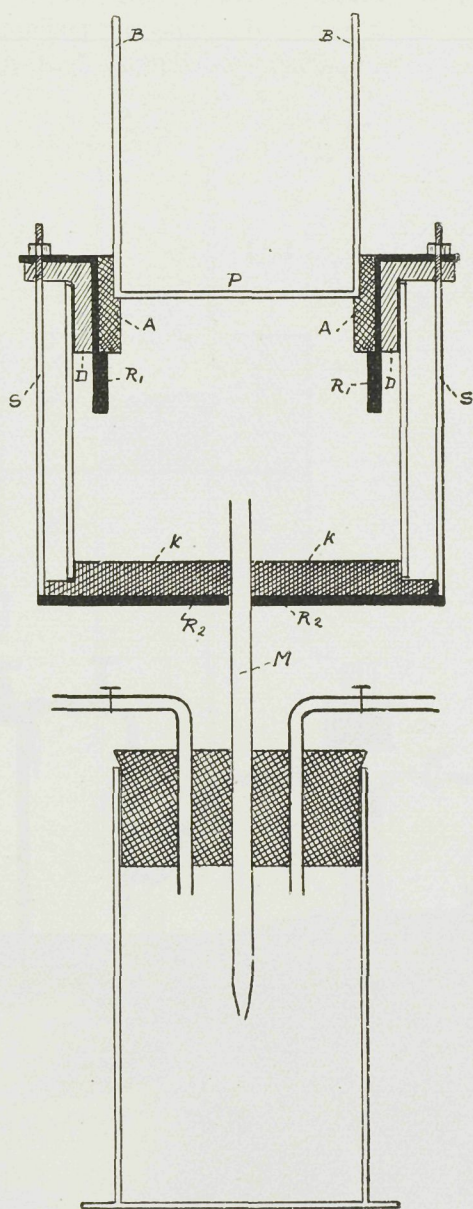


Fig. 3.

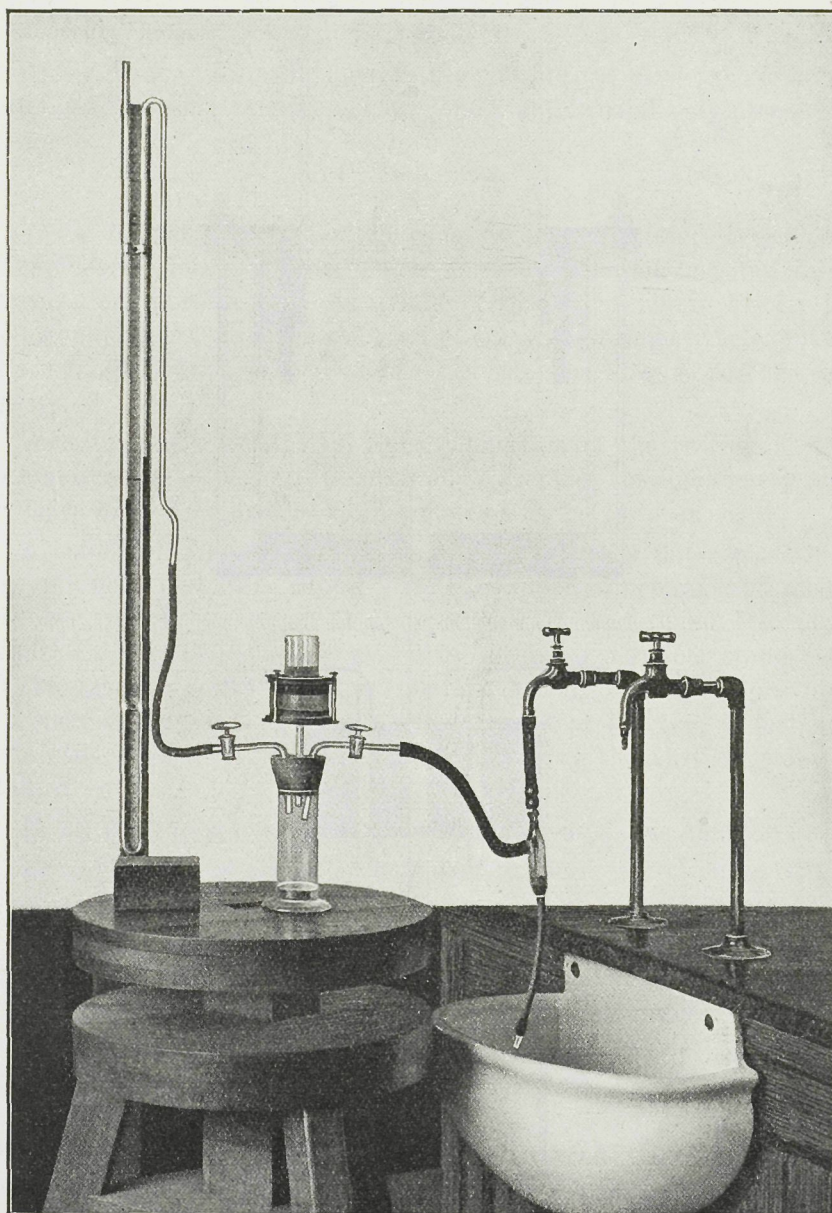


fig. 3a.

The duration of the test varied, of course, with the magnitude of the negative capillary pressure. If it was to be expected that the latter would be great, the subpressure per minute was raised by 4 mm.

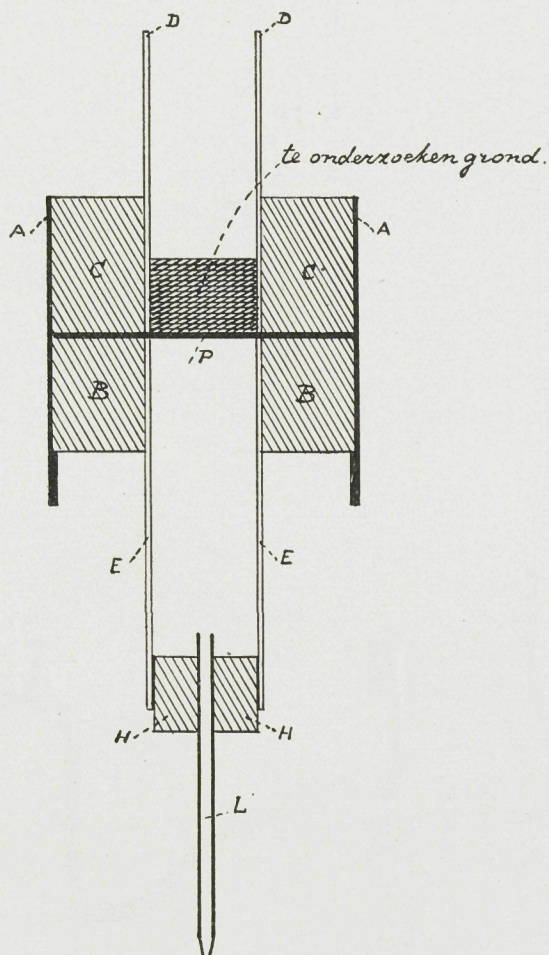


Fig. 4.

(mercury), in the other cases by 2 mm. (mercury); experience suggested this. Moreover, the tap C (fig. 2) was occasionally closed, where upon the dropping ceased and equilibrium was reached.

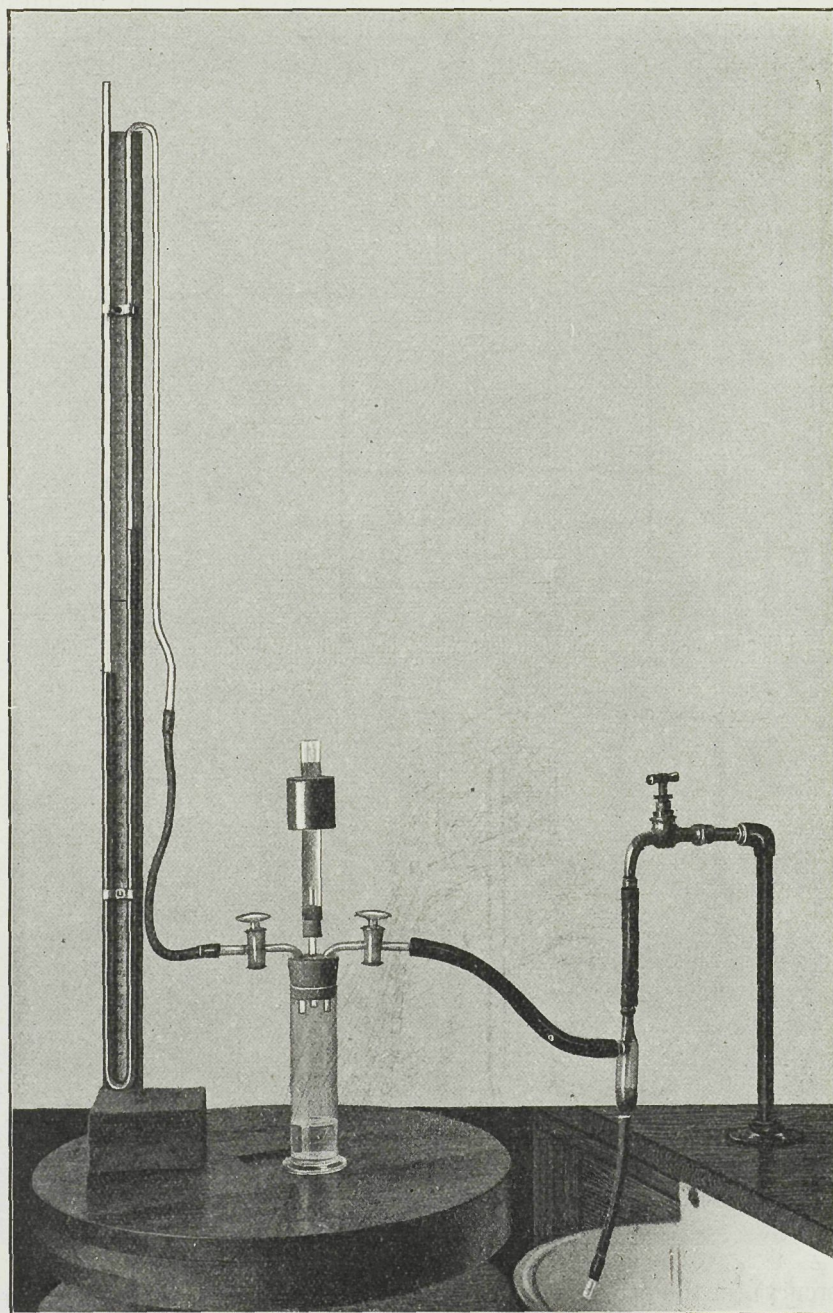


fig. 4a.

With this apparatus the negative capillarity pressure, or, as the case may be, the capillary rise, may be determined in a comparatively short time. The greatest duration of a test in my investigations was $2\frac{1}{2}$ hours. With the capillarimeters of Versluys and Gardner each test takes several days. Moreover, a rise can be determined which is greater than the height of a laboratory.

As set forth in Chapter I, too many objections exist to the determination of the capillary rise in tubes with dry soil, in consequence of which the results obtained deviate as a rule widely from the reality. In addition to this, the tests, supposing that the maximum rise actually were reached, become practically impossible to carry out.

While working with the capillarimeters in figs 2, 3 and 4, it was found that the appearance of air could very distinctly be observed if the apparatus was placed wrong side up in clamps. Before an apparatus was inverted a slight subpressure was first induced in the ordinary position. The expression for the neg. cap. pressure then becomes

$$13.6 n - h.$$

According to some investigators, the diameter of the tubes has an influence on the rise. Rotmistrov (32), for instance, finds a greater rise with a smaller diameter. Wadsworth and Smith (33) find just the contrary. The latter investigators find for instance with one and the same soil 85.6 cm. with a diameter of 1 square inch and 141.8 cm. with a diameter of 25 square inches. No explanation of this phenomenon is given. The writer would suggest the following: As the rise in the dry soil becomes greater, the internal diminution of pressure increases, and consequently the volume of the already moist mass decreases. If the soil above this does not sink, a crack will form, which will prevent a further rise. Tubes of small diameter have per unit of diameter a relatively greater surface, so that the cracks have a better chance of remaining.

A decrease of volume with increased subpressure was repeatedly noticeable in my tests.

The internal diameter of the cylindrical tubes of soil varied from 1 to 6 cm., and, although special attention was paid to this, no influence of this on the results obtained was observed.

*

Chapter III

Results of the investigation. Influence of the thickness of the soil layer. Minimum-and maximum negative capillarity pressure

Two kinds of soil were tested, and also fractions of different sizes¹). The mechanical composition²) of the two kinds of soil was as follows:

	Humus	Fraction I ($< 2 \mu$)	Fraction II ($2-16 \mu$)	Clay	Fraction IIIa ($16-76 \mu$)	Fraction IIIb ($76-152 \mu$)	Fraction IV ($152-200 \mu$)	Sand	CaCo ₃
Sea-sand ...	0%	0.96%	0.73%	1.69%	0.84%	73.61%	20.51%	94.96%	3.35%
Soil B. 504 ..	0.11%	3.42%	2.58%	6.00%	42.45%	48.77%	2.21%	93.43%	0.11%

Several trials were made to find out whether different results were obtained by pounding with a wooden pestle than by letting the soil sink into a thin layer of water. This proved not to be the case.

Each test of a fraction or a kind of soil was begun with the determination of the negative capillarity pressure of an extremely thin layer of soil (indicated in the tables by $0 + \text{mm.}$) The layer was later made thicker and thicker. The results obtained with sea-sand, soil B. 504 and the fractions III and II of soil B. 29, are shown in table 1. The negative capillarity pressure is expressed in all the tables in cm. water-pressure.

Table 1 shows that the negative capillarity pressure increases with the thickness of the layer, and that it reaches a maximum with a thickness of about 20 mm. in the case of the soils and fractions tested.

In future the negative capillarity pressure found with an extremely thin layer of soil will be called the minimum negative capillarity pressure (D_{mi}), and that with a layer of 20 mm. or more the maximum negative capillarity pressure (D_{ma}).

¹) These were kindly given me by Dr. D. J. Hissink, Director of the Institute for Soil Science, Groningen.

²) From Dr. D. J. Hissink.

The relation between the thickness of the layer of soil and the negative capillarity pressure is shown graphically in figs 5 to 8 inclusive. The thicknesses of the layers are plotted out as abscissae and the negative capillarity pressure as ordinates. These capillarity curves show clearly the relation already noticed.

As is to be expected, both D_{mi} and D_{ma} , increase, when the content of fine particles becomes greater. This is shown in Table 2.

It may here also be noted that the influence of the thickness of the layer of soil renders it improbable that Versluys will find the same results with the two ways in which he determines the capillary movement. (See p. 6.)

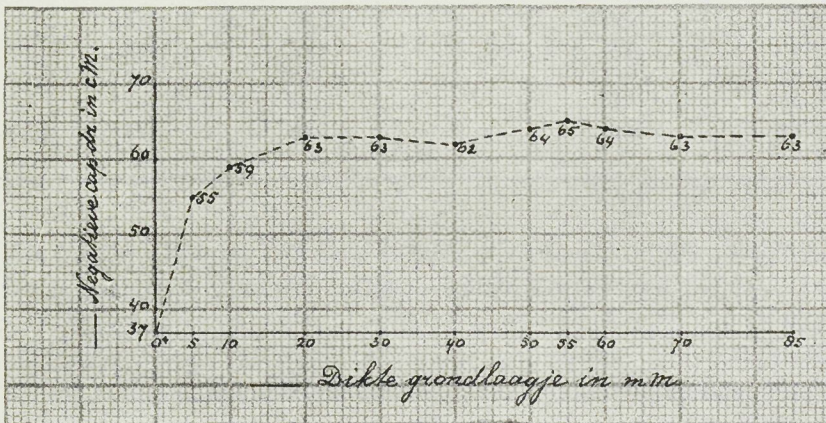


fig. 5.
Capillarity curve of sea-sand.

The following considerations are an attempt to explain this phenomenon:

In an extremely thin layer, viz., one in which the thickness is not greater than the dimensions of the soil particles, capillaries of various widths will occur. Let us represent this as is shown fig. 9 a, by means of 4 very short capillary tubes increasing in width from left to right, and called respectively capillaries of the 1st, 2nd, 3rd and 4th order. The menisci are for the sake of simplicity indicated at the middle of height by straight lines.

Table 1. Negative capillarity pressure of sea-sand,

Sea-sand			B. 504		
Thickness of soil-layer in mm.	Negative capillarity pressure in cm.	Number of observations	Thicknes of soil-layer in mm.	Negative capillarity pressure in mm.	Number of observations
0 +	37	20	0 +	70	25
5	55	12	10	104	12
10	59	8	15	120	10
20	63	7	20	122	8
30	63	8	30	125	10
40	62	5	55	124	9
50	64	6	60	123	6
55	65	6	70	123	8
60	64	7	80	121	7
70	63	5	130	125	6
85	64	6	140	124	5

Table 2
Values of D_{mi} and D_{ma} (in cm)

	D_{mi}	D_{ma}
Sea-sand	37	63
B. 504	70	123
Fraction III (B. 29).....	93	180
Fraction II (B. 29)	260 ¹⁾	750 ¹⁾

¹⁾ In the tests with fraction II (B. 29) results were found at first which differ but little from the results with fraction III (B. 29). Before, therefore, the soil was put into the capillarimeter, it was boiled in water, to which a few drops of ammonia were added. It was found that the results found for D_{mi} and D_{ma} were then as shown in Table 2. It follows that soil particles before the treatment with ammonia were combined into complexes; between these complexes there were larger openings, which made the negative capillarity pressure smaller.

It was found during the tests that the amount of ammonia did not need to be accurately measured.

The sea-sand, soil B. 504 and fraction III (B. 29) were also treated with ammonia, but here the results remained the same.

soil B 504, a fraction III and a fraction II

Fraction III (B. 29)			Fraction II (B. 29)		
Thickness of soil-layer in mm.	Negative capillarity pressure in cm.	Number of observations	Thickness of soil-layer in cm.	Negative capillarity pressure in mm.	Number of observations
0 +	93	21	0 +	260	10
1	126	5	1	400	8
2	146	6	3	490	7
5	164	7	6	650	5
10	170	4	7	735	4
18	176	5	8	750	4
20	180	4	18	748	5
30	179	5	26	750	4

It will be plain that in such a layer the widest capillary will determine the negative capillarity pressure of the entire layer, since air will appear during the test, as soon as downward force (= weight of water-column, or = weight of water-column + subpressure, or = subpressure — weight of water-column) becomes greater than the negative capillarity pressure of the menisci of the 4th order. The minimum neg. cap. pressure (D_{mi}) was therefore determined for an extremely thin layer.

In a somewhat thicker layer of soil, 2 layers of capillaries may occur, one above the other, and in such a way that a capillary of a particular order alternates with a capillary of another order, as shown in fig. 9b. In the same way fig. 9c and 9d show how the capillaries may occur alternately in 3 and in 4 layers respectively.

In a test arranged as in fig. 9b, air will appear, as soon as the negative capillarity pressure of the meniscus of the 3rd order is exceeded; in fig. 9c the same applies to a meniscus of the 2nd order, and in fig. 9d for a meniscus of the 1st order. In the last case will be found therefore the maximum neg. cap. pressure (D_{ma}).

If an arrangement of the layers is made, as indicated in fig. 9, then an increase in the thickness from one layer to 4 layers is sufficient to get from D_{mi} to D_{ma} . From the representation given it can also be

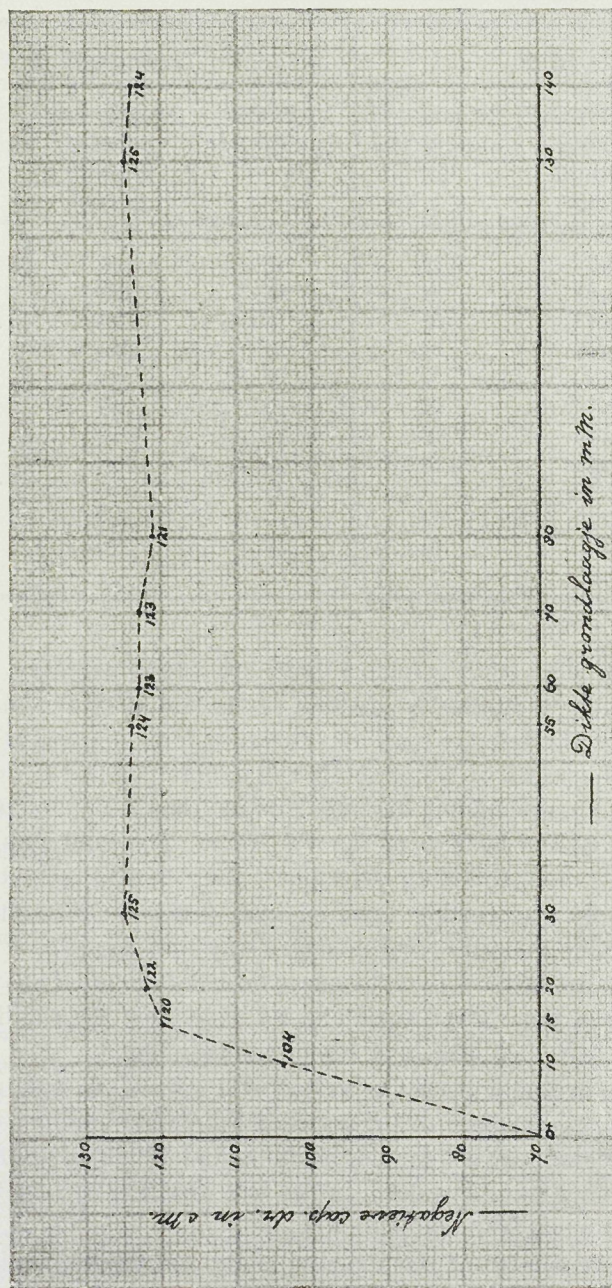


fig. 6. Capillarity curve of soil B. 504.

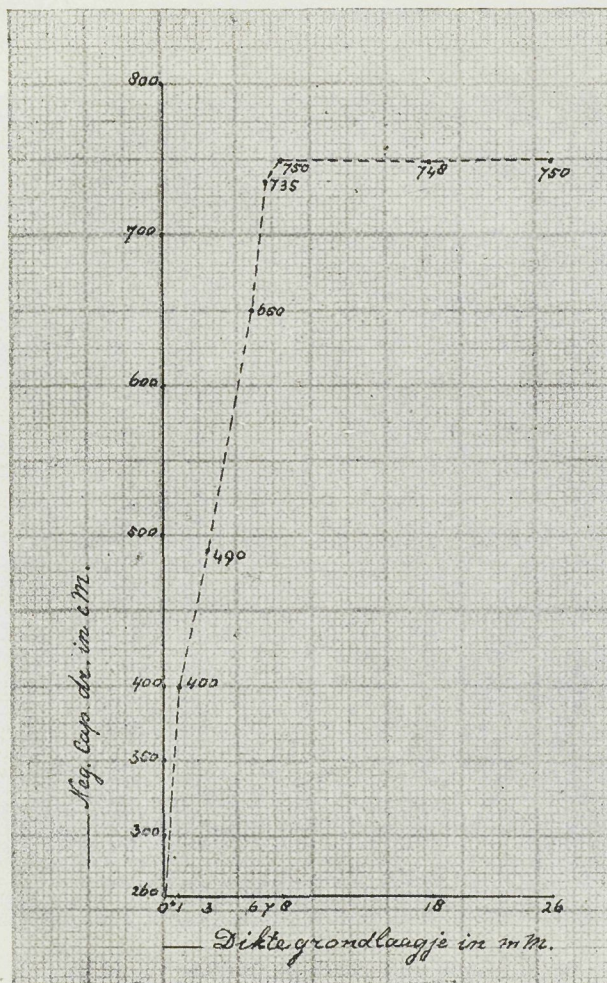


fig. 7.

Capillarity curve of fraction II (B. 29).

seen why the capillary surface in a heterogeneous soil must be an uneven surface. This also becomes evident with a different arrangement of the capillaries, as e. g. in fig. 9d'.

In order to confirm the correctness of the representation given, copper discs were made, 40 mm. in diameter and 1 mm. thick, in which

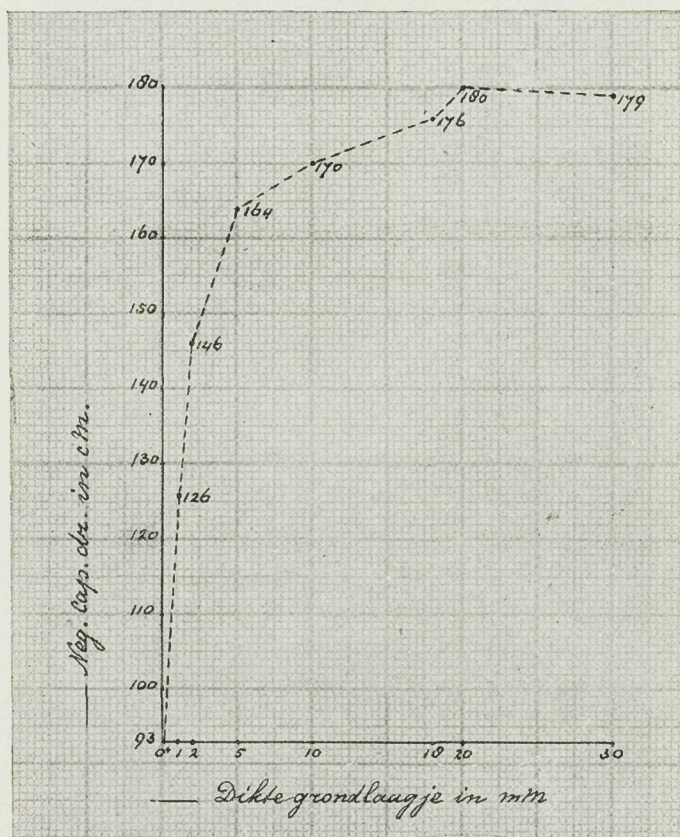


fig. 8. Capillarity curve of fraction III (B. 29).

in 4 right-angled sectors of 1, $\frac{1}{2}$, $\frac{1}{4}$ and $\frac{1}{8}$ mm. were bored in the manner shown in fig. 10. The middle and a 5 mm. strip along the edge were not perforated. The plates were put into a rubber ring, which fitted exactly into a glass tube.

In testing with one disc (fig. 11, I) D_{mi} must be found, corresponding to the 1 mm. holes in sector 4. If a 2nd disc, after a turning

through 90 degrees, is placed on the first one (II on I), then a neg. cap. pressure D_2 is found, corresponding to the $\frac{1}{2}$ mm. holes in sector 3. If a 3rd disc (III on I + II) is used, a D_3 will be found, corresponding to the $\frac{1}{4}$ mm. holes in sector 2, and if a 4th disc is used (IV on III + II + I) D^{ma} will be found, corresponding to the $\frac{1}{8}$ mm. holes.

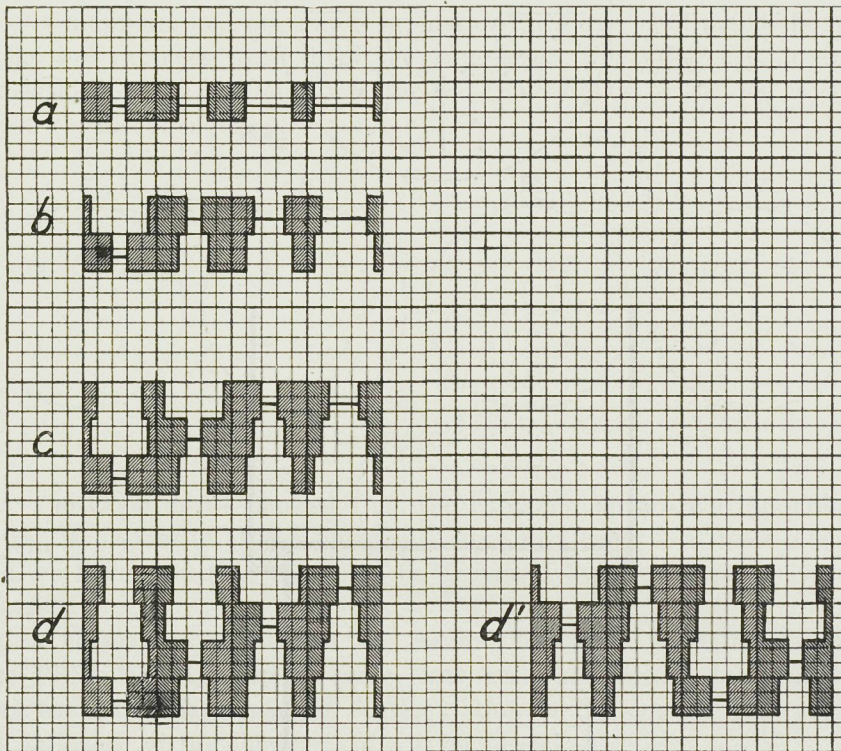


fig. 9.

And as a matter of fact the results turned out to be in accordance with the theory, although the absolute values found for the neg. cap. pr. did not perfectly correspond to the capillarity-constant for pure water, which is 7.5. The reason for this is probably that the holes in the sectors 1, 2, 3, and 4, were not quite of the diameters stated.

23.5, 11.5, 6.2 and 2.9 cm. were found for D_{ma} , D_3 , D_2 and D_{mi} respectively, whilst 24, 12, 6 and 3 ought to have been found respectively, if the holes had been exactly of the dimensions stated.

From mathematical point of view it might be important to know which number of discs would be sufficient to reach D_{ma} .

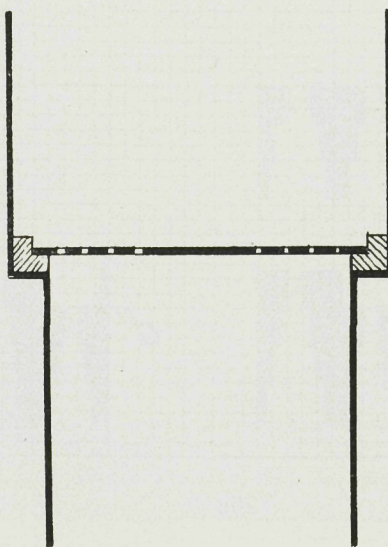
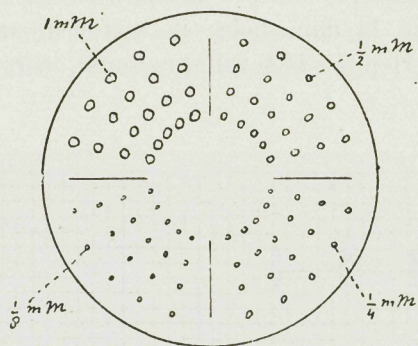


fig. 10.

Suppose that a particular soil is a mixture of 4 homogeneous fractions,

a fraction a_1 with a neg. cap. pr. = 80 cm.

„ „ a_2 „ „ „ „ „ = 60 „

„ „ a_3 „ „ „ „ „ = 40 „

„ „ a_4 „ „ „ „ „ = 20 „

and further that in each thin layer the same amount of space is occupied by the capillaries of each of these fractions, then, in a test with a very thin layer a neg. cap. pr. = 20 cm. will be found. With an increase of thickness the values 40 cm., 60 cm. and 80 cm. will be reached consecutively. The capillary surface is then uneven. If the thickness of the layer increases still further, then the neg. cap. pr. will undergo no further change.

A minimum and maximum capillarity pressure would not be found if the soil particles were all of the same size. The differences in the dimensions of the particles, i. e. the heterogeneity of the soil is the cause of this phenomenon.

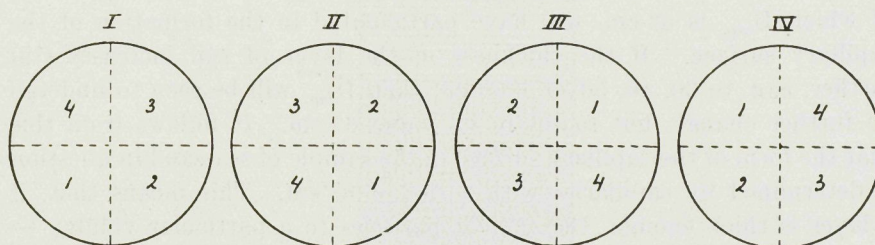


fig. 11.

The experiments showed that the capillary surface corresponding to D_{ma} is present in all the soils tested even in a layer of at most 2 cm., and we have seen that this is to be explained by the heterogeneity of the soil.

A closer consideration of the results obtained e. g., with sea-sand (see Table 1), may help to make clear what has already been shown with the aid of the schematic representation in figs. 9a—d, concerning the influence of the thickness of a layer of soil.

Now these results are that with an extremely thin layer of soil a neg. cap. pr. of 37 cm. was found by means of the capillarimeter, with a layer of 5 mm. a neg. cap. pr. of 55 cm., with a layer of 10 mm. 59 cm. and with a layer of 20 mm. 63 cm. This means that, as long as the layer has a thickness of practically 0 mm., the capillary surface is formed by menisci situated in one and the same horizontal plane, the neg. cap. pr. of which is determined by the cap. pr. of the widest capillaries.

As soon as the layer of 5 mm. thickness is taken, it is seen that the phreatic surface may fall to 55 cm., before air appears in the capillarimeter. Before this moment is reached, the menisci will fall in all the capillaries of which the neg. cap. pr. is less than 55 cm. The capillary

surface is only maintained at the original height, i. e., approximately on the surface of the layer of soil, in the smallest capillaries. The capillary surface has now become the enveloping surface of menisci which are situated at various levels in the layer of soil of 5 mm. The capillary surface is now, therefore, an unevenly curved surface, with a cap. pr. of 55 cm. in the hollows.

In a thicker layer of soil, viz. 10 mm., the state of equilibrium in the apparatus, with a rise of 59 cm., is seen to cease. Just before this, therefore, a capillary surface must have been formed with a neg. cap. pr. of 59 cm. at the lowest points; the unevenness in this surface has increased.

Finally, in an experiment with a layer of soil 20 mm. thick, menisci of which $D_{\text{cap.}}$ is 63 cm. will have participated in the formation of the capillary surface. If the thickness of the layer of soil increases still further, e. g. to 30, 40, 50 or 60 mm., then $D_{\text{cap.}}$ will be seen to undergo no further change, but to retain its value 63 cm. It follows from this that the form of the capillary surface in the sample of sea-sand in question is determined by capillaries with a rise of 63 cm. This means that, if a layer is thick enough, the smaller particles to a particular volume — of which more in Chapter V — determine the maximum rise.

Chapter IV

The water content in and above the capillary zone.

Sejunction water. Funicular action.

With the help of the heterogeneity of the soil and the D_{mi} and D_{ma} caused by it, it is possible to show that there is a connection between the content of water in and the thickness of the capillary zone and the manner in which the capillary level moves.

In the tests with capillarimeters, as we have seen, a fall of the capillary surface was artificially produced. In nature this sinking occurs owing to the water being withdrawn from the capillary zone in consequence of evaporation through plants and directly, or by ground water being drained off (e. g. by means of drainage).

If before the beginning of a fall of the capillary surface all the capillary spaces and cavities underneath it were filled with water, then the content of water in a layer of which the thickness is determined by D_{ma} (e. g. the capillary zone) will, when the sinking has taken place and a state of equilibrium has been reached, be as high as possible, as all the capillary spaces and cavities in that zone remain filled with water. The water content at all parts of the capillary zone then agrees with

the absolute water-capacity (31, 32, 33), by which is to be understood the pore-volume minus the volume of the canals.

If on the other hand there is a rise of the capillary surface by adjustment from below, then the water content in the capillary zone is quite different from what it is with a sinking. This may be seen from the following: If a column of soil 80 cm. thick, consisting of a mixture of 4 homogeneous fractions with rises of 20, 30, 40, 60 and 80 cm., is placed on a water-surface (fig. 12), then all pores to a height of 20 cm. will be filled¹⁾. In a test of this soil for the determination of

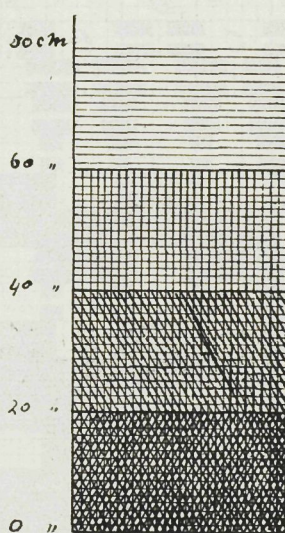


fig. 12.

D_{mi} and D_{ma} 20 and 80 cm. respectively should be found for this. From 20 to 40 cm. the capillaries of the 4th order²⁾ are not filled, from 40 to 60 cm the capillaries of the 4th and 3rd orders are not filled, and from 60 to 80 cm. those of the 4th, 3rd and 2nd orders are not filled.

Moreover, in the case in question, only a few capillaries of the 1st order of the topmost layer were filled. This may be seen from the schematic representation of the capillaries of the 4th order in fig. 13. Each layer in this figure is in reality built up out of various combinations of the 4 above mentioned capillaries, which vary in size. The capillary spaces are also connected with each other laterally. In order not to

¹⁾ See the restriction on p. 42.

²⁾ Capillaries of the 1st order correspond to a rise of 80 cm., those of the second order to a rise of 60 cm., etc.

make the representation of the subject under consideration too complicated, these connecting capillaries are supposed to be of equal width. A displacement of water will naturally always take place laterally from a wider to a narrower capillary. In the division of the capillaries represented in fig. 13, the capillaries indicated in a grey tint will become filled with water. In the layer from 60 to 80 cm. only a few capillaries of the 1st order will therefore be filled.

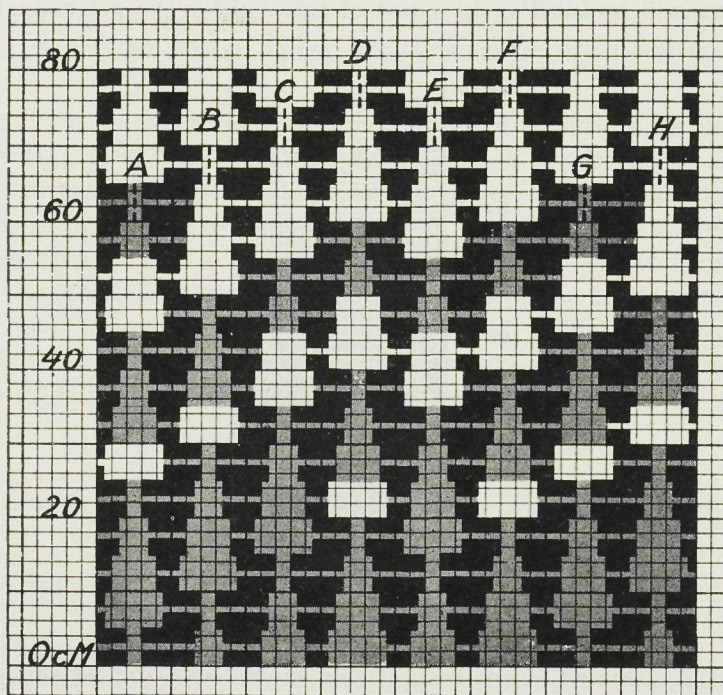


fig. 13.

It can further be seen that the water content diminishes from below upwards. The irregular course of the capillary surface is also shown in the figure. The radii of curvature of the menisci in A and G (the highest points of the cap. surf.) are not yet as small as possible, or, in other words, the negative capillarity pressure is not yet at its maximum.

Under natural conditions such a filling of the capillary surface will e. g. occur when water is run into ditches. Near the ditch the cap. surf. will then rise in the manner indicated, but also farther away from the ditch — where the phreatic surface, owing to the letting in of water, afterwards rises — such a capillary rise will take place. The same thing

also occurs with subsoil irrigation, for instance as a result of the retention of water in drains by means of "Stauventiele".

If the column of soil under consideration is placed for a time in water, in such a way that the surface of the water is as high as or higher than the surface of the soil, then all the capillaries will be filled with water, at least, if no capillaries filled with air are enclosed. If the column is now drawn up 80 cm. out of the water, then the capillary surface will be formed in the capillaries A, B, C, D, E, F, G and H (fig. 13), and it will be as nearly as possible on the surface of the soil. The negative capillarity pressure of the cap. surf. is then practically at its maximum, i. e. equal to D_{ma} .

With the above explanation of the occurrence of a minimum and maximum negative capillarity pressure, as a result of the heterogeneity of the soil, the reason is also indicated why the capillary zone in the same soil can be of various thicknesses and the content of water at various levels in that zone is sometimes equal and sometimes different.

From the following it will be seen that the heterogeneity of the soil is also the reason why water may occur above the capillary zone in a condition of equilibrium, in which capillaries are completely filled.

If for the wider of 2 capillary tubes, which are connected with each other (fig. 14), e. g. $D_{cap.} = 65$ and for the narrower $D_{cap.} = 120$ cm., and if the phreatic surface is 65 cm. below the top, then, at the top of both tubes, a meniscus will be formed, which can carry a column of water 65 cm. high. If the phreatic surface falls 30 cm. (= length of the wide capillary), i. e. to 95 cm., then the meniscus in the wide capillary will fall 30 cm., whilst the one in the narrow capillary will remain at the same height, but the radius of curvature of this meniscus will become smaller. As soon, however, as the water in the lefthand tube has fallen 30 cm., a part of the water in the righthand tube will be cut off from the rest. A sejunction has taken place, in which the water is shut in between the menisci M_1 and M_2 , of which the negative capillarity pressure is 120 and 90 cm. respectively. The neg. cap. pr. of the meniscus M_3 is 65, and only after the phreatic surface has fallen another $120 - 65 = 55$ cm., will M_3 fall also. It is evident that such a fall has no influence on the sejunction; this remains where it arose.

How sejunctions can arise in a network of capillaries is shown in fig. 15. The numbers placed in the capillaries indicate the greatest negative capillarity pressure which is possible there. If we assume that at first all the capillaries are filled with water, then the water, as soon as the phreatic surface has fallen to a depth $= 65 + h$, will have dis-

appeared over a layer h cm. thick, out of all the capillaries in which the number 65 is placed, excepting the one which forms the connection between the two capillaries in which the number 90 is placed. In the case under consideration two sejuncts have arisen. The water in the sejuncts is indicated by sloping hatching. The levels at which the water in the capillaries C_1 , C_2 and C_3 remains, are indicated in the figure.

In the same way it may be supposed that, in a natural soil, with continuous falling of a phreatic surface, sejuncts will arise out of the elevations of the capillary zone, as we supposed them to have arisen

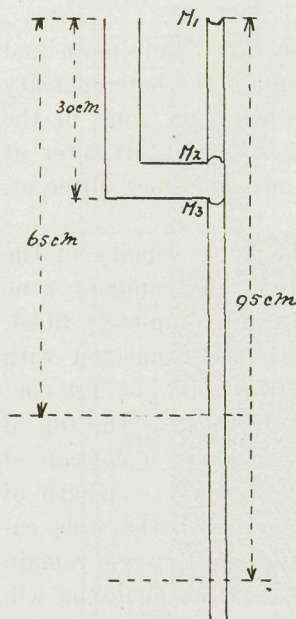


fig. 14.

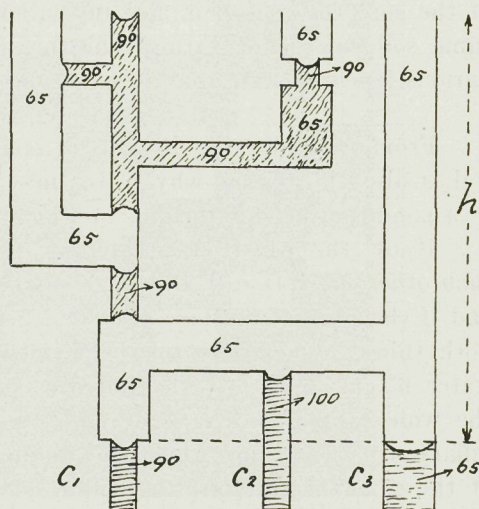


fig. 15.

in the speculation on pp. 21 and 22 regarding the influence of the heterogeneity in the neg. cap. pr. For to maintain the connection of the water in the elevations of the entire capillary mass of water, the neg. cap. pr. would have to keep on increasing in the capillary surface which bounds the elevations.

The existence of sejuncts is a ready explanation of the phenomenon that above the capillary level a fairly large water content may be present in a state of equilibrium. Consider, e. g., high-lying sandy soils, in which the phreatic surf. and the cap. surf. occur far below the surface of the soil, and in which the crops in long periods of drought or slight rainfall are none the less in an astonishingly good condition.

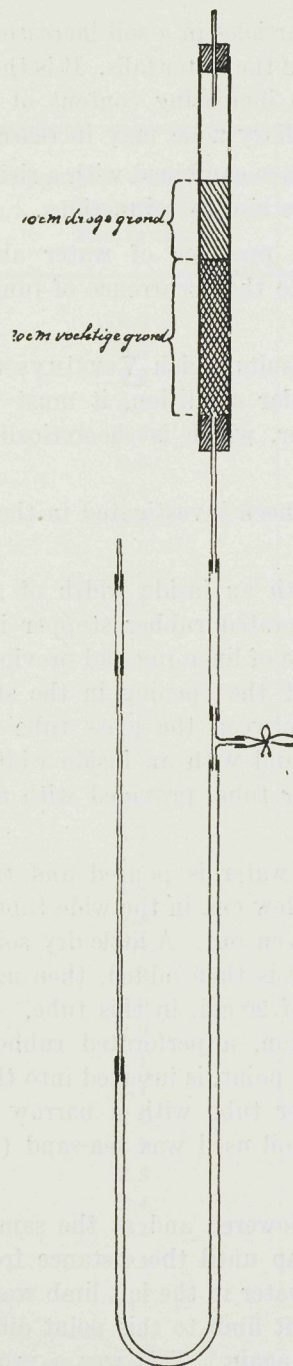


fig. 16.

Translation of the Dutch letter-
presses:

droge grond = dry soil
vochtige grond = moist soil

As the amount of finer particles in a soil increases, more sejunctions will arise above the cap. surf., if the latter falls. It is then conceivable that from this fact alone with an increasing content of finer particles the water content above the capillary zone may increase.

A rise of the phreatic surface combined with a rising of the capillary surface will naturally not give rise to sejunctions.

In Versluys' view the presence of water above the capillary surface can only be ascribed to the occurrence of funicular and perhaps also of pendular water.

In consequence of the results which Versluys (37) reports in his investigations into the funicular condition, it must be concluded that such a condition of the water, which is theoretically explicable, may actually occur in the soil.

The funicular action has been investigated in the following manner by the writer himself:

A glass tube (fig. 16) with an inside width of 28.5 mm. is closed at its bottom end by a perforated rubber stopper into which a glass tube has been inserted. A piece of linen rag had previously been wrapped round this, so that it covered the opening in the stopper. A rubber tube forms the connection between the glass tube and another tube placed in a vertical position and with an inside width of 4 mm. A 1 piece is inserted in the rubber tube, provided with a rubber tube and clamp.

Into the left hand tube water is poured and this tube is drawn up until the water has risen a few cm. in the wide tube, care being taken that the air is completely driven out. A little dry soil is then put into the wide tube. A little water is then added, then again dry soil, etc., until there is a layer of soil of 20 cm. in this tube. In order as far as possible to prevent evaporation, a perforated rubber stopper with a glass tube, drawn out to a fine point, is inserted into the top of the tube. For the same reason a rubber tube with a narrow opening is forced round the 4 mm. tube. The soil used was sea-sand ($D_{mi} = 37$ cm. and $D_{ma} = 63$ cm.).

The left hand tube was lowered and at the same time water was removed by opening the clamp until the distance from the surface of the soil to the surface of the water in the left limb was 37 cm. A lowering of the waterlevel in the left limb to this point did not result in the water in it beginning to rise again. This was a proof that the value for D_{mi} found is correct for sea-sand.

Table 3

Time in days	Apparatus with 10 cm. dry soil (a) Fall in cm.	Apparatus without dry soil (b) Fall in cm.
0	0.0	0.0
1	0.1	0.1
2	0.2	0.1
3	0.3	0.1
4	0.3	0.1
5	0.4	0.2
6	0.4	0.3
7	0.5	0.3
8	0.5	0.3
9	0.6	0.4
10	0.7	0.4
11	0.9	0.6
12	1.1	0.7
13	1.2	0.7
14	1.2	0.7
15	1.3	0.8
16	1.5	0.9
17	1.6	1.0
18	1.7	1.0
19	1.7	1.0
20	1.8	1.1
21	1.8	1.1
22	1.9	1.1
23	1.9	1.2
24	2.0	1.2
25	2.0	1.3
26	2.1	1.3
27	2.1	1.4
28	2.2	1.4
29	2.2	1.5
30	2.3	1.5
31	2.4	1.6
32	2.4	1.6
33	2.4	1.6

The distance was then increased to 75 cm. When this distance was reached, the water in the narrow tube again began to rise, owing to capillary water being withdrawn from the soil. The distance was therefore again brought up to 75 cm.; the result was a fresh rising of the water in the narrow limb, and this was repeated until, about 2 hours after the last rising had been induced, no further rising was observed, a state of hydrostatic equilibrium having come about.

A layer of dry sea-sand, 10 cm. thick, was now introduced into the wide tube. While this was being done the tube was gently tapped, until no further diminution in volume was observed.

At the same time an experiment was begun in exactly the same way with a second apparatus, no dry sand, however, being put on top.

The experiment consisted in the level of the water in both apparatuses being taken every day for 33 days; at the same time the temperature was noted. In table 3 are recorded 34 levels, each of which was taken about the middle of a day. In addition to these observations in the middle of the day, a large number, in total 186, were made in connection with the fluctuations in the temperature, of which more will be found on pp. 29 and 30.

Table 3 shows that in case a in 33 days the fall of the phreatic surface was 2.4 cm., and in case b 1.6 cm. By putting dry soil on top the fall thus becomes 0.8 cm. greater.

Incidentally it was noted that prior to the placing of dry soil on the top the capillary surface in case a had fallen $75 - 63 = 12$ cm. below the surface of the ground.

In order to get an insight into the water-displacement in the soil, the tube was carefully inverted at the end of the 33 days. The 10 cm. of soil placed on the top slid out, except the lowest 4 mm. This latter was carefully loosened, collected and weighed. The other soil was also weighed. Drying and weighing was then repeated. Before drying, the weight of the entire layer of 10 cm. of soil was 100.120 grams, and after drying, 100 grams. The dry soil had therefore absorbed 0.120 grams water. The separate weighings showed that this 0.120 grams occurred almost exclusively in the lowest 4 mm. This rise of 4 mm. was externally imperceptible.

The fall of 1.6 cm. in case b must be ascribed to evaporation. In case a, also a similar fall cannot be caused in any other way than by evaporation. The amount of water displaced with a fall of 1.6 cm. is 0.200 grams.

In case a water was absorbed by the dry soil. The fall of 2.4 cm. is equal to a displacement of water of 0.300 grams, so that in case a at

least 0.100 grams must have been absorbed by the dry soil. According to the weighing a somewhat greater amount was absorbed (0.120 grams).

The experiment shows that a funicular action has taken place, but that the quantity of water which was thereby displaced and fixed is extremely small. A calculation shows that the quantity in 33 days is equivalent to $\frac{1}{5}$ mm. of rain. Versluys also says that the movement in the funicular zone is extremely slow.

It is not impossible that, in case a, evaporation followed by condensation took place. That water has come at the end of the experiment into the superimposed soil can hardly be attributed exclusively to this, as in that case the fall in case a would certainly not have been greater than in case b.

The previously reported observations in connection with the temperature have shown that the latter affected the height of the phreatic surface. This connection was distinctly observable on days with fairly great fluctuations of temperature. The observations in Table 4 were made on June 27th 1927.

Table 4

Temperature on June 27 th , 1927	Fall in cm.
6.30 a. m. 12.5° C.	—
8.30 „ 13.2 „	0.0
10.00 „ 14.0 „	— 0.1
12.00 „ 14.2 „	— 0.1
3.45 p.m. 16.2 „	— 0.2
4.45 „ 16.0 „	+ 0.1
7.30 „ 15.9 „	+ 0.1
10.30 „ 15.2 „	0.0

The table shows that with a rise in temperature the water rises and vice versa. The cause of this phenomenon is to be found in the decrease of the capillarity constant in consequence of the decreased viscosity with a rise in temperature.

It seems to the writer that the above mentioned may be one of the causes for the fact that drainage systems carry off less water at night or even cease to run (38, 39).

Conclusion: The presence of water above the capillary zone is chiefly the result of the heterogeneity of the soil, owing to which sejunctions arise. The plants may be benefited by the sejunction-water, which is to be regarded as

a reserve supply. Funicular and pendular water also supply needed water, but the funicular movement is so extremely slow that an adjustment of funicular water is practically of no moment.

Chapter V

The relation between the size of the soil particles and the negative capillarity pressure

As is shown by Table 2 (p. 16), $D_{mi II}$ of fraction II (2—16 μ) is greater than $D_{ma III}$ of fraction III (16—152 μ). This is only what is to be expected:

For the largest particles of fraction II, i. e. those of 16 μ , may have contributed to the existence of $D_{mi II}$, whilst the smallest particles of fraction III, i. e. those of 16 μ , may have contributed to the existence of $D_{ma III}$. It will therefore depend on the number of particles of 16 μ in each of the fractions II and III whether the values for $D_{mi II}$ and $D_{ma III}$ vary. As the number of particles of 16 μ in both fractions increases, the difference in negative capillarity pressure must get smaller and vice versa. For, generally speaking, the rule must hold good for two adjacent fractions A and B, of which A is the smaller: $D_{mi A} > D_{ma B}$, and for the particles which form the boundary between the two fractions, the negative capillarity pressure is consequently $D_{cap.} < D_{mi A}$ and $> D_{ma B}$.

One would therefore be inclined to conclude from Table 2 that the neg. cap. pr. of a homogenous soil, consisting of particles of 16 μ , must have a value of between 180 and 260 cm.

If — continuing this train of reasoning — n fractions of consecutive sizes are tested, then it is possible to determine for $n - 1$ sizes of particles, within what limits the negative capillarity pressure fluctuates. Theoretically the negative capillarity pressure is inversely proportional to the width of the capillaries and therefore also to the size of the particles. Such an inverse proportion would then have been apparent in the results. From the following it will be seen that the reasoning would only hold good if the limits between the fractions could be sharply defined and the fractions in practice could be divided according to these limits.

Dr. D. J. Hissink, Director of the Institute for Soil Science at Groningen was kind enough to make a number of such fractions for me. This was done with the apparatus of Atterberg, by means of the various sinking-times. The fractions are called fraction a, fraction b, etc.; below are given the dimensions:

fraction a: 16—32 μ ,
 „ b: 32—48 μ ,
 „ c: 48—64 μ ,
 „ d: 64—96 μ ,
 „ e: 96—128 μ .

The tests again showed that a layer of soil of 20 mm. at the most was sufficient to reach D_{ma} . The number of determinations for each neg. cap. pr. was in every case 10. The results follow in Table 5¹⁾:

Table 5. Values for D_{mi} and D_{ma} (in cm.)

	D_{mi}	D_{ma}
Fraction a. 16—32 μ	124	225
„ b. 32—48 μ	100	129
„ c. 48—64 μ	78	114
„ d. 64—96 μ	56	89
„ e. 96—128 μ	40	80

The results of the tests are at first sight surprising. For D_{mi} of a fraction is always smaller than D_{ma} of the fraction next in size.

This unexpected result must be due to the limits of the fractions being different from those found by mechanical soil-analysis.

All the fractions were therefore measured microscopically. Through the kindness of Dr. K. Zijlstra, Director of the 5th Department of the State Agricultural Experimental Station at Groningen, I was enabled to make the measurements at his laboratory. The method followed was the same as the one²⁾ used by Dr. Zijlstra in measuring farina grains. It should however be stated here that a portion of each fraction, after being dried, was vigorously shaken up with pure glycerine; a drop of the suspension thus obtained was transferred by means of a pipette to a slide.

Two measurements were made of each particle, viz. the greatest dimension and one at right angles to this, so that the product of the two measurements represented pretty well the visible surface projected into a horizontal plane. As it was found, during the consideration of the figures obtained, that, by considering only the greatest dimensions, corresponding results were obtained to those given by a consideration of both dimensions, the following exposition is based on the greatest dimensions alone.

The number of particles of each fraction measured was at least 1000.

¹⁾ D_{mi} and D_{ma} were also determined after the 5 fractions were boiled in water, to which a few drops of ammonia were added. Only in fraction a an influence was perceptible. ²⁾ To be published eventually.

In the Tables 6, 7, 8, 9 and 10, which refer respectively to the fractions a, b, c, d and e, the particles are in each case arranged in column A in classes of 2—4, 4—6, etc. The class-limits in the columns A of the Tables 6, 7 and 8 are given in micra, and in those of the Tables 9 and 10 in 1.5625 micra: thus e. g. 40—42 in Table 6 means 40—42 μ and in Table 9 40 to 42 $\times 1.5625 \mu$. In the columns B are found the numbers of particles of each class; column C contains the class-averages, raised to the third power; column D is the product of B and C (expressed in 1000 μ) and column E is the summation of column D.

Table 6
Relates to fraction a

A	B	C	D	E
0—2	133	1	0	0
2—4	85	27	2	2
4—6	69	125	8	10
6—8	36	343	12	22
8—10	21	729	15	37
10—12	12	1331	15	52
12—14	7	2197	15	67
14—16	6	3375	20	87
16—18	4	4913	19	106
18—20	9	6859	61	167
20—22	11	9261	101	268
22—24	24	12167	292	560
24—26	46	15625	718	1278
26—28	54	19683	1062	2340
28—30	49	24389	1195	3535
30—32	72	29791	2144	5679
32—34	72	35937	2587	8266
34—36	86	42875	3687	11953
36—38	66	50653	3342	15295
38—40	79	59319	4686	19981
40—42	77	68921	5031	25012
42—44	62	79507	4929	29941
44—46	74	91125	6743	36684
46—48	43	103823	4464	44148
48—50	35	117649	4117	45265
50—52	48	132651	6267	51532
52—54	43	148877	6401	57933
54—56	28	166375	4658	62591
56—58	17	185193	3148	65739
58—60	17	205379	3491	69230
60—62	12	226981	2723	71953
62—64	10	250047	2500	74453
64—66	5	274625	1373	75826
66—68	3	300763	902	76728
68—70	4	328509	1314	78032
70—72	1	357911	357	78389
72—74	3	389017	1147	79536
74—76	2	421875	843	80379
76—78	3	456533	1369	81748
78—80	1	493039	493	82241
84—86	1	614125	614	82855

$\frac{1}{32} (2589)$
 $\frac{1}{16} (5178)$
 $\frac{1}{8} (10357)$
 $\frac{1}{6} (13809)$
 $\frac{1}{4} (20714)$
 $\frac{1}{3} (27618)$

$\frac{1}{32} (2589)$
 $\frac{1}{16} (5178)$
 $\frac{1}{8} (10357)$
 $\frac{1}{6} (13809)$
 $\frac{1}{4} (20714)$
 $\frac{1}{3} (27618)$

Table 7
Relates to fraction b

A	B	C	D	E
4— 6	5	125	0	
6— 8	1	343	0	
8— 10	1	729	0	
16— 18	1	4913	4	4
18— 20	2	6859	13	17
20— 22	1	9261	9	26
22— 24	1	12167	12	38
24— 26	1	15625	15	53
26— 28	4	19863	78	131
28— 30	6	24389	146	277
32— 34	7	35937	251	528
34— 36	5	42875	214	742
36— 38	8	50653	405	1147
38— 40	9	59319	533	1680
40— 42	26	68921	1781	3461
42— 44	22	79507	1749	5120
44— 46	43	91125	3918	9128
46— 48	35	103823	3633	12761
48— 50	48	117649	5647	18408
50— 52	51	132651	6765	25273
52— 54	53	148877	7890	33163
54— 56	63	166375	10481	43644
56— 58	29	185193	5370	49014
58— 60	42	205379	8625	57639
60— 62	90	226981	20428	78067
62— 64	46	250047	11502	89569
64— 66	62	274625	17026	106595
66— 68	46	300763	13834	120429
68— 70	40	328509	13140	133569
70— 72	38	357911	13600	147169
72— 74	37	389017	14393	161562
74— 76	36	421875	15187	176749
76— 78	19	456533	8674	185423
78— 80	29	493093	14298	199721
80— 82	37	531441	19663	219384
82— 84	13	571787	7433	226817
84— 86	25	614125	15353	242170
86— 88	8	658503	5268	247438
88— 90	7	704969	4934	252372
90— 92	8	753571	6028	258400
92— 94	10	804357	8043	266443
94— 96	6	857375	5144	271587
96— 98	4	912673	3650	275237
98— 100	5	970299	4851	280088
100— 102	2	1030301	2060	282148
102— 104	1	1092727	1092	283240
104— 106	2	1157625	2315	285555
110— 112	4	1367631	5470	291025
112— 114	1	1442897	1442	292462
116— 118	3	1601613	4804	297271
120— 122	1	1771561	1771	299042
124— 126	1	1953125	1953	300995

$\frac{1}{32}$ (9406)
 $\frac{1}{16}$ (18812)
 $\frac{1}{8}$ (37624)
 $\frac{1}{6}$ (50166)
 $\frac{1}{4}$ (75249)
 $\frac{1}{3}$ (100332)

Table 8
Relates to fraction c

A	B	C	D	E
20—22	1	9261	9	9
28—30	3	24389	73	82
36—38	1	50653	50	132
38—40	2	59319	118	250
44—46	2	91125	182	432
46—48	1	103823	103	535
48—50	7	117649	823	1358
50—52	2	132651	265	1623
52—54	4	148877	595	2218
54—56	12	166375	1996	4214
56—58	14	185193	2592	6806
58—60	14	205379	2875	9681
60—62	35	226981	7944	17625
62—64	28	250047	9501	27126
64—66	42	274625	11534	38660
66—68	36	300763	10827	49487
68—70	43	328509	14125	63612
70—72	45	357911	16105	79717
72—74	35	389017	13615	93332
74—76	47	421875	19828	113160
76—78	38	456533	17348	130508
78—80	41	493039	20214	150722
80—82	79	531441	41983	192705
82—84	42	571787	24015	216820
84—86	56	614125	34391	251211
86—88	36	658503	23705	274916
88—90	42	704969	29608	304524
90—92	46	753571	34664	339188
92—94	29	804357	23325	362513
94—96	35	857375	30007	392520
96—98	29	912673	26467	418987
98—100	19	970299	18435	437422
100—102	37	1030301	38121	475553
102—104	22	1092727	24039	499582
104—106	22	1157625	25467	505049
106—108	10	1225043	12250	517299
108—110	11	1295029	14245	531544
110—112	5	1367631	6838	538382
112—114	10	1442892	14428	552810
114—116	4	1520875	6083	558893
116—118	2	1601613	3203	562096
118—120	2	1685159	3370	565462
120—122	9	1771561	15944	581406
122—124	3	1860867	5582	586988
124—126	4	1953125	7812	594800
126—128	3	2048383	6145	600943
128—130	2	2146689	4293	605238
130—132	2	2248091	4496	609734
132—134	4	2352637	9410	619144
136—138	1	2571353	2571	621715
140—142	1	2803221	2803	624518
144—146	1	3048625	3048	627566
148—150	1	3307949	3307	630873
154—156	1	3723875	3723	634596

$\frac{1}{32}$ (19831)
 $\frac{1}{16}$ (39662)
 $\frac{1}{8}$ (79324)
 $\frac{1}{6}$ (105766)
 $\frac{1}{4}$ (158649)
 $\frac{1}{3}$ (211532)

Table 9
Relates to fraction c

A	B	C	D	E
32—34	2	35937	71	71
34—36	2	42875	85	156
36—38	2	50653	101	257
38—40	3	59319	177	434
40—42	6	68921	413	847
42—44	17	79507	1351	2198
44—46	14	91125	1275	3473
46—48	17	103823	1764	5237
48—50	16	117649	1882	7119
50—52	40	132651	5306	12425
52—54	40	148877	5955	18380
54—56	43	166375	7154	25534
56—58	40	185193	7407	32941
58—60	44	205379	9036	41977
60—62	95	226981	20993	62970
62—64	66	250047	16503	79473
64—66	61	274625	16752	96225
66—68	55	300763	16541	112766
68—70	49	328509	16056	128822
70—72	58	357911	20758	149580
72—74	49	389061	19061	178641
74—76	46	421875	19406	198047
76—78	43	456533	19630	217677
78—80	22	493039	10846	228523
80—82	49	531441	26040	254563
82—84	21	571787	12007	266570
84—86	14	614125	14739	281309
86—88	16	658503	8936	290245
88—90	15	704969	10574	300819
90—92	21	753571	15824	316643
92—94	11	804357	8847	325490
94—96	11	857375	9431	334921
96—98	12	912673	10952	345873
98—100	3	970299	2910	348783
100—102	12	1030301	12363	361146
102—104	3	1092727	3278	364424
104—106	2	1157625	2315	366739
106—108	1	1225043	1225	367964
108—110	2	1295029	2590	370554
112—114	2	1442897	2885	373439
114—116	2	1520875	3041	376480
116—118	2	1601613	3203	379683
118—120	2	1685159	3370	383053
120—122	1	1771561	1771	384824
122—124	1	1860867	1860	386684
124—126	1	1953125	1953	388137

$\frac{1}{32}$ (12145)
 $\frac{1}{16}$ (24290)
 $\frac{1}{8}$ (48580)
 $\frac{1}{4}$ (97159)
 $\frac{1}{3}$ (129536)

$\frac{1}{32}$ (12145)
 $\frac{1}{16}$ (24290)
 $\frac{1}{8}$ (48580)
 $\frac{1}{4}$ (97159)
 $\frac{1}{3}$ (129546)

Table 10
Relates to fraction e

A	B	C	D	E
32—34	1	35937	35	35
40—42	5	68921	344	379
42—44	3	79507	238	617
44—46	7	91125	637	1254
46—48	1	103823	103	1357
48—50	9	117649	1058	2415
50—52	10	132651	1326	3741
52—54	14	148877	2084	5825
54—56	21	166375	3493	9318
56—58	17	185193	3148	12811
58—60	25	205379	5134	17945
60—62	47	226981	10668	28613
62—64	24	250047	6001	34614
64—66	49	274625	13456	48070
66—68	36	300763	10827	58897
68—70	39	328509	12811	71708
70—72	61	357511	21832	93540
72—74	56	389017	21784	115324
74—76	49	421875	20671	135995
76—78	36	456533	16435	152430
78—80	43	493039	21200	173630
80—82	68	531441	37137	209767
82—84	47	571787	26873	236640
84—86	44	614125	27021	263661
86—88	43	658503	28315	291976
88—90	30	704969	21149	313125
90—92	31	753571	23360	336485
92—94	19	804357	15282	351767
94—96	25	857375	21434	373201
96—98	33	912673	30118	403319
98—100	12	970299	11643	414962
100—102	27	1030301	27818	442780
102—104	11	1092727	12019	454779
104—106	13	1157625	15049	469848
106—108	7	1225043	8575	478223
108—110	8	1295029	10360	488583
110—112	5	1367631	6838	495421
112—114	4	1442897	5771	501192
114—116	4	1520875	6083	507275
116—118	5	1601613	8008	515283
118—120	6	1685159	10110	525393
120—122	7	1771561	12400	537793
122—124	3	1860867	5582	543375
124—126	3	1953125	5859	549234
126—128	2	2048383	4096	553330
128—130	2	2146689	4293	557623
132—134	1	2352637	2352	559975
134—136	1	2460375	2460	562435
140—142	4	2803221	11212	573647

$\frac{1}{32}$ (17926)

$\frac{1}{16}$ (35853)

$\frac{1}{8}$ (71706)

$\frac{1}{6}$ (95608)

$\frac{1}{4}$ (143412)

$\frac{1}{3}$ (191216)

$\frac{1}{32}$ (17926)

$\frac{1}{16}$ (35853)

$\frac{1}{8}$ (71706)

$\frac{1}{6}$ (95608)

$\frac{1}{4}$ (143412)

$\frac{1}{3}$ (191216)

We have already had occasion to remark in general that the smallest particles affect the value of D_{ma} and the largest particles the value of D_{mi} . It is further evident that the very smallest particles of a fraction do not determine the value of D_{ma} if the total volume of these particles only forms a small portion of the total volume of the fraction; but they may participate in the formation of the capillary surface. The class 2—4 μ of fraction a in Table 6 has a relative volume of 2, whilst the total volume of fraction a is 82855; the particles of this class alone will therefore not suffice to give rise to a continuous capillary surface. If the volume 8 of the next larger class 4—6 μ is added, in consequence of which the total volume will be 10, then in the particles of both classes together no continuous capillary surface can arise either. Continuing in this way with the addition of classes, a volume must at last be reached in which a continuous capillary surface will arise. The largest particles which have contribution to this, determine the value of D_{ma} .

The value of D_{mi} will not be affected by the particles of the very largest class, if they only take up a small part of the total volume of the fraction. The class 84—86 μ of fraction a in Table 6 takes up a volume of 614 to the total volume of 82855. The particles of this class cannot affect the formation of a continuous capillary surface with a neg. cap. pressure D_{mi} . Through the addition of decreasing classes the volume of the larger particles becomes at last so great that the capillary surface already spoken of arises; in this capillary surface the radius of curvature of the menisci is determined by the dimensions of the class last added. The dimensions of this smallest class therefore determine the value of D_{mi} .

Conclusion: In any fraction (or in any soil) D_{ma} is determined by the largest of a certain volume of small particles and D_{mi} by the smallest of a certain volume of large particles.

If in fraction a for this particular volume of small particles we take $\frac{1}{3}$ of the total volume ($= 27618$), then the particles with the greatest dimensions, as is shown by Table 6, are 42 μ . If further $\frac{1}{4}$, $\frac{1}{6}$, $\frac{1}{8}$, $\frac{1}{16}$ and $\frac{1}{32}$ are taken consecutively, then the largest particles are respectively 40, 36, 34, 32 and 28 μ .

If in fraction a for this particular volume of large particles we take $\frac{1}{3}$ of the total volume, then Table 6 shows that the particles with the smallest dimensions are 52 μ . If we now take further $\frac{1}{4}$, $\frac{1}{6}$, $\frac{1}{8}$, $\frac{1}{16}$ and $\frac{1}{32}$ respectively, then the smallest particles are respectively 54, 58, 62, 68 and 74 μ .

Fractions b, c, d and e have been treated in the same way. In the Tables 6, 7, 8, 9 and 10, is in each case indicated to the right of column E where the limits of the volumes taken are situated.

The results of this method are collected in Table 11.

Table 11

Fractions	Negative cap. pr.		Vol. of the smallest particles (expressed in terms of the total volume), of which the greatest determine D_{ma} , and also the volume of the largest particles (expressed in terms of the total vol.), of which the smallest determine D_{mi}											
			$\frac{1}{3}$		$\frac{1}{4}$		$\frac{1}{6}$		$\frac{1}{8}$		$\frac{1}{16}$		$\frac{1}{32}$	
	D_{ma} (in cm)	D_{mi} (in cm)	Greatest dimension of the smallest particles (in μ)	Smallest dimension of the largest particles (in μ)	Greatest dimension of the smallest particles (in μ)	Smallest dimension of the largest particles (in μ)	Greatest dimension of the smallest particles (in μ)	Smallest dimension of the largest particles (in μ)	Greatest dimension of the smallest particles (in μ)	Smallest dimension of the largest particles (in μ)	Greatest dimension of the smallest particles (in μ)	Smallest dimension of the largest particles (in μ)	Greatest dimension of the smallest particles (in μ)	Smallest dimension of the largest particles (in μ)
a	225	124	42	52	40	54	36	58	34	62	32	68	28	74
b	129	100	64	80	60	82	58	88	54	92	50	102	46	112
c	114	78	82	98	80	102	74	108	70	114	66	126	62	132
d	89	56	109	128	103	138	97	144	94	150	84	159	78	181
e	80	40	125	150	119	156	113	166	106	178	100	191	91	200

An increase of the neg. cap. pr. must accompany a decrease of the dimensions of the particles, by which the pressure is determined. If each of the columns in Table 11 above which $\frac{1}{3}$, $\frac{1}{4}$, $\frac{1}{6}$, $\frac{1}{8}$, $\frac{1}{16}$ and $\frac{1}{32}$ stand, is compared with the column at the head of which is the neg. cap. pr., it will be seen that: The closest agreement exists between the $\frac{1}{8}$ column and the one of the negative cap. pr. For the line running from the smallest dimension 34μ over the constantly increasing di-

Table 12

Negative cap. pr.		Size of particles		Product	
D _{ma}	D _{mi}	in relation to D _{ma}	in relation to D _{mi}	of D _{ma} and correspond. size	of D _{mi} and correspond. size
225		34 ¹⁾		7650	
	124		62 ¹⁾		7688
129		54		6966	
	100		92		9200
114		70		7980	
	78		114		8892
89		94		8366	
	56		150		8400
80		106		8480	
	40		178		7120

mensions 54, 62, 70 μ , etc., to the greatest one 178 μ follows the same course as the line running from the greatest neg. cap. 225 cm. over the pr. constantly decreasing numbers 129, 124, 114 cm. etc. to the smallest one (40 cm.). No other combination is to be found in which the agreement is so striking.

Conclusions: 1. The maximum negative capillarity pressure is governed by particles of such dimensions that the volume of all the smaller ones is $\frac{1}{8}$ of the total volume.

2. The minimum negative capillarity pressure is governed by particles of such dimensions that the volume of all the larger ones is $\frac{1}{8}$ of the total volume.

In Table 12 are shown once more: in the first column the negative capillarity pressure, in the second column the dimensions of the soil particles which give rise to the pressure, and a third column with the products of the numbers in the first and in the second columns.

¹⁾ As stated on p. 48, the measurements of the particles were made after drying. It may be suggested that in consequence of this, complexes of particles are formed, with the result that the values found for the dimensions of the particles are too great. In this connection it may be observed that complexes of particles were not observed under the microscope. Furthermore the two upper products in Table 12 (7650 and 7688) would have to be greater than the average value (8074); they are however smaller.

The products of pressure and dimensions vary from 7000 to 9200. The average value of the 10 products is 8074. This figure 8074 is to be regarded as a constant value of the product of the negative capillarity pressure (expressed in cm.) and the corresponding dimension of the particles (expressed in μ). From this follows the relation:

$$D_{\text{cap.}} = \frac{c}{d},$$

in which $c = 8074$

d = size of particles in μ .

By the use of this formula, when D_{mi} and D_{ma} of a soil have been determined, that soil may be divided into 3 fractions.

Thus we find, for the 4 soils and fractions treated of in Chapter III, the following:

Sea-sand. Found: $D_{\text{mi}} = 37$ and $D_{\text{ma}} = 63$.

Consequently: $\frac{1}{8}$ of the volume $> 218 \mu$ ($= 8074 : 37$)

$\frac{1}{8}$ " " " $< 128 \mu$ ($= 8074 : 63$)

$\frac{6}{8}$ " " " 128 to 218μ .

B. 504. Found: $D_{\text{mi}} = 70$ and $D_{\text{ma}} = 123$.

Consequently: $\frac{1}{8}$ of the volume $> 115 \mu$ ($= 8074 : 70$)

$\frac{1}{8}$ " " " $< 65 \mu$ ($= 8074 : 123$)

$\frac{6}{8}$ " " " 65 to 115μ .

Fraction III (B 29). Found: $D_{\text{mi}} = 93$ and $D_{\text{ma}} = 180$.

Consequently: $\frac{1}{8}$ of the volume $> 87 \mu$ ($= 8074 : 93$)

$\frac{1}{8}$ " " " $< 45 \mu$ ($= 8074 : 180$)

$\frac{6}{8}$ " " " 45 to 87μ .

Fraction II (B 29). Found: $D_{\text{mi}} = 260$ and $D_{\text{ma}} = 750$.

Consequently: $\frac{1}{8}$ of the volume $> 31 \mu$ ($= 8074 : 260$)

$\frac{1}{8}$ " " " $< 11 \mu$ ($= 8074 : 750$)

$\frac{6}{8}$ " " " 11 to 31μ .

I found during the microscopic measurements of the fractions a, b, c, d and e, that the dimensions calculated according to the decantation method (application of Stoke's formula) varied greatly from the actual ones. Thus calculations from the Tables 6, 7, 8, 9 and 10 give:

Fraction a (16—32 μ after decantation)	26 % of the number	< 16 μ ;	0 % of the volume	< 16 μ
	55 % " " "	> 32 μ ;	93 % " " "	> 32 μ
	19 % " " "	16—32 μ ;	7 % " " "	16—32 μ
Fraction b (32—48 μ after decantation)	2 % " " "	< 32 μ ;	0 % " " "	< 32 μ
	83 % " " "	> 48 μ ;	96 % " " "	> 48 μ
	15 % " " "	32—48 μ ;	4 % " " "	32—48 μ
Fraction c (48—64 μ after decantation)	1 % " " "	< 48 μ ;	0 % " " "	< 48 μ
	88 % " " "	> 64 μ ;	96 % " " "	> 64 μ
	11 % " " "	48—64 μ ;	4 % " " "	48—64 μ
Fraction d (64—96 μ after decantation)	1 % " " "	< 64 μ ;	0 % " " "	< 64 μ
	66 % " " "	> 96 μ ;	84 % " " "	> 96 μ
	33 % " " "	64—96 μ ;	16 % " " "	64—96 μ
Fraction e (96—128 μ after decantation)	14 % " " "	< 96 μ ;	3 % " " "	< 96 μ
	40 % " " "	> 128 μ ;	70 % " " "	> 128 μ
	46 % " " "	96—128 μ ;	27 % " " "	96—128 μ

It will be seen that in the fractions a, b, c, d and e respectively only 7 %, 4 %, 4 %, 16 % and 27 % of the total volume is within the limits given according to the decantation method, and that particularly the upper limits are far exceeded. In the above summary the percentages of the number are also included. It is plain that, to judge the degree of accuracy of the figures the figures of the volumes ought to be taken; there may be a large number of particles within the limits, whilst this only forms a comparatively small part of the total volume. Thus Hissink (41) found, in two fractions II (2—16 μ after decantation) and in two fractions IIIa (16—76 μ after decantation) the following:

in fraction	II of sea-clay	90.6 % of the number between	2—16 μ ,
" "	II " boulder-clay	93.5 % " " "	2—16 μ ,
" "	IIIa " sea-clay	91.3 % " " "	16—76 μ ,
" "	IIIa " boulder-clay	85 % " " "	16—76 μ .

On calculating the volumes, however, I found:

in fraction	II of sea-clay	30 % of the volume between	2—16 μ ,
" "	II " boulder-clay	54 % " " "	2—16 μ ,
" "	IIIa " sea-clay	85 % " " "	16—76 μ ,
" "	IIIa " boulder-clay	46 % " " "	16—76 μ .

The attention would also immediately be arrested by such great differences if D_{mi} and D_{ma} were determined. For instance, for fraction IIIa of boulder-clay it would be found that $D_{ma} = 192$ cm. and $D_{mi} = 71$ cm.

whilst $\frac{1}{8}$ of the volume $< 42 \mu$, $\frac{1}{8}$ of the volume $> 114 \mu$ and $\frac{6}{8}$ of the volume is between $42-114 \mu$.

Resumé: In 5 fractions, which, according to the results obtained by decantation, should have been close together, D_{mi} and D_{ma} were determined. The values found indicated that the limits stated were not correct. Microscopic measurements then made also showed this to be the case. As a result of these measurements it became possible to formulate a relation between the negative capillarity pressure and the corresponding dimensions of the soil particles, and with the aid of this to make a division of the soil into three fractions.

Chapter VI

Concluding remarks on capillary action in connection with the heterogeneity of the soil and the presence of cavities and canals

With capillary rise in soil in the laboratory it was observed by others that the maximum water-content was not found just above the phreatic surface, but at some distance above it. McLaughlin was one of the first to call attention to this (42). Wadsworth and Smith (43) found that the maximum water-content occurred above the phreatic surface at a distance which varied from 12 to 23 % of the total rise. In results, reported by Garola (44), the same phenomenon may also be noted.

It will again be found that this phenomenon is also connected with the heterogeneity of the soil.

The flow through capillary tubes is indicated by Poisseuille (45) by the following relation:

$$Q = N \frac{SD^4}{L},$$

in which Q is the quantity of liquid which flows through a capillary tube in a particular time; N is a constant, depending on the nature of the liquid and on the temperature; S is the difference in pressure at the ends of the capillary tube; D is the diameter and L the length of the tube.

The velocity $v = \frac{Q}{F}$ (F = section), consequently

$$v = \frac{4N}{\pi} \cdot \frac{SD^2}{L}.$$

Further the capillary rise $h = \frac{4\sigma}{D}$ and $= \frac{4\sigma}{h}$, so that

$$v = \frac{4N}{\pi} \cdot \frac{S \left(\frac{4\sigma}{h} \right)^2}{L} = K \frac{S}{h^2 L}.$$

If the water has risen to a height L above the phreatic surface, then the difference in pressure S at the beginning and end point is $h - L$, and the velocity at the level of L

$$v_L = K \frac{h - L}{h^2 L} \dots \dots \dots (I)$$

For a homogenous soil with a capillary rise h_1 the following applies

$$v_{1L} = K \frac{h_1 - L}{h_1^2 L} \dots \dots \dots (II)$$

and for another homogeneous soil with a capillary rise h_2

$$v_{2L} = K \frac{h_2 - L}{h_2^2 L} \dots \dots \dots (III)$$

Suppose $v_{1L} = v_{2L}$, then

$$K \frac{h_1 - L}{h_1^2 L} = K \frac{h_2 - L}{h_2^2 L} \text{ and } L = \frac{h_1 h_2}{h_1 + h_2} \dots \dots (IV)$$

In words: at a height above the phreatic surface which is equal to the product of the rises, divided by the sum of the rises, the velocity of rise in two homogeneous soils is the same. —

Below this level, as may be deduced from (II) and (III), the velocity is smaller in the soil with a greater rise than in the one with a smaller rise.

In two homogeneous soils the velocity of rise is at first greatest in the one consisting of the largest particles, and that until a height is reached, determined by the relation (IV); above this height the velocity of rise is greater in the soil consisting of the smallest particles.

In a heterogeneous soil consisting of a mixture of these homogeneous soils, the water-content will consequently gradually increase from the phreatic surface to a height L above it. For all the capillaries are filled to that height. Of the smaller capillaries the smallest number will be filled at first. As the rise increases, this number becomes greater, as the velocity of rise in the smaller capillaries decreases relatively less rapidly than in the large capillaries. At the height L the greatest water-content is to be expected. Above that height all the small capillaries are filled and fewer and fewer large capillaries. The water-content therefore diminishes, to the height h_2 , the

height in the coarsest soil. From here to the height h_1 , all the small capillaries only are filled and the water-content is therefore constant.

A heterogeneous soil is in reality to be regarded as a mixture of a very large number of homogeneous ones. A similar reasoning to the above is also applicable to it, in order to show that the analogous phenomenon may occur here. This does not mean that under natural conditions, after a capillary rise at some distance above the phreatic surface, the water-content will be at its maximum. Thus the presence of a quantity of water, which is already in a layer of soil before a capillary rise takes place in this layer, will frequently result in the non-occurrence of an increase followed by a decrease in the water-content of the capillary zone. After a rise in dry soil, however, the phenomenon will occur, at least if there are no cavities or canals.

It is difficult to get all the capillary spaces in a soil entirely filled with water. The following experiment shows this:

5 tubes 10 cm. long and with an internal diameter of 1.62 cm. were filled, being tapped during the filling, with soil B. 504; the tubes were closed at the bottom by means of a piece of copper gauze covered with a piece of linen and held fast by a copper cylinder. From the specific gravity and the apparent specific gravity the pore-volume was calculated to be 42.7%. The tubes were placed in water in such a way that the surface was at the same level as the surface of the soil. The tubes were repeatedly taken out of the water, quickly dried and weighed. The weighings of the 5 tubes gave the following average results (Table 13).

Table 13

After	Water absorbed		Air	
	in % of the total volume	in % of the pore-space	in % of the total volume	in % of the pore-space
5 min.	35.1	82.2	7.6	17.8
3 hrs.	35.3	82.7	7.4	17.3
9 "	37.3	87.3	5.4	12.7
24 "	37.3	87.3	5.4	12.7
29 "	37.5	87.8	5.2	12.2
32 "	37.0	86.7	5.7	13.3
48 "	37.0	86.7	5.7	13.3
52 "	36.8	86.2	5.9	13.8
58 "	36.8	86.2	5.9	13.8
72 "	36.8	86.2	5.9	13.8
240 "	36.8	86.2	5.9	13.8

In this experiment therefore, 13.8% of the total pore-space remained filled with air. Owing to the small length of the soil-column in which the capillary movement took place, it will have been more especially the smallest capillaries which were not filled with water.

There are probably other factors also which help to cause the presence of air, such as the presence of an air-skin¹⁾ round dry soil-particles, but it is impossible to ascribe the occurrence of fairly large quantities of air to this alone; the influence of the heterogeneity of the soil is here especially felt.

Very little statistical material is found in the literature of the subject regarding the distribution of the water in a capillary zone. Moreover, in view of the phenomenon treated of in the foregoing, very little value can be attached to these data, unless at the same time it is shown or can be ascertained what proportion of the total pore-space is filled with water and in what way the filling of the capillary spaces has taken place. In the case of the previously mentioned experiments of Wadsworth and Smith we are only told that at particular heights above the phreatic surface a maximum water-content occurs.

That the way in which the water has got into the capillary spaces affects the water-content found later, is shown by King's test (46). King filled tubes with sand of various grain-sizes, and states how the saturation with water took place.: "When the apparatus was filled with sand, water was slowly introduced from the bottom, so as to expel the air, until the pieces were full..." It is hard to conceive that the air was in this way completely displaced and the capillary spaces entirely filled with water. The tubes were then left alone for a long time, during which no evaporation could take place, and the water-content was then determined at various levels. King expresses the water-content in percentages of the dry weight, so that it is impossible to see what the relative filling of the pore-spaces at various levels was. But apart from this, it is possible to infer from the figures that the air was not completely displaced. In the case of sand Nr. 60 King finds at a level of

— (See p. 294) —

At a height of 15—18 inches therefore the maximum water content occurs. If the air had at the beginning been completely displaced, then the water-content should have been approximately equal to this below the height of 15—18 inches; the differences run, however, up to 5%.

¹⁾ The presence of an air-skin will be one of the reasons why in the determination of the specific gravity of the soil the results found are too low.

24—21	inches	13.52	weight	% of water
21—28	„	23.57	„	„ „ „
18—15	„	27.93	„	„ „ „
15—12	„	23.61	„	„ „ „
12—9	„	22.46	„	„ „ „
9—6	„	22.76	„	„ „ „
6—3	„	22.88	„	„ „ „
3—0	„	23.54	„	„ „ „

It may also be deduced from Poisseuille's law that the velocity with which the water sinks in capillaries is independent of the thickness of the sinking layer of water and proportional to the square of the diameter, or, which comes to the same thing, inversely proportional to the capillary rise. This relation naturally only holds good if in consequence of the sinking of water no air comes under pressure, as this impedes the sinking. As long as there is any water on the soil the water will sink at a greater rate.

In two homogenous soils in which the size of the particles is as 1 to 2, the rates of the sinking velocities will be to each other as 4 to 1. In a natural, i. e. heterogeneous, soil the water will move rapidly downwards especially in the larger capillary spaces, whereas small capillary spaces will at first remain filled with air. During the sinking sejunctions will at the same time occur. After a sinking capillary water-column has passed the narrow air-filled capillaries, these will be able, by means of capillary action, to fill themselves entirely or partially with water from less narrow capillaries, at least if the air can escape.

During the sinking the amount of sinking water decreases. As soon as the capillary surface has been reached, the phreatic surface immediately rises to the same extent as the height of the sinking water-column. In connection with this, it is difficult to accept as correct what has been italicized by the writer in the following passage from the so-called Lovink Commission (47):

“The water which falls on the surface of the soil will, under the influence of gravity, so far as the interstices admit of this, percolate to the lower soil-layers. Only that part, however, of the surface water will reach a deeper soil-layer, which is not retained in a higher one. If, therefore, a soil, from which part of the capillary water has been withdrawn as a result of evaporation, is saturated with surface-water, this will first of all be retained in the topmost layers until these have reached the limit of their capillary saturation; water will

then percolate to deeper layers and with a sufficient supply of water, this percolation will continue until the last layer of soil above the ground-water is in a state of capillary saturation. Only then will a state of affairs arise, in which further adjustment of surface-water will give rise to a rising of the ground-waterlevel."

The decrease in the amount of sinking water may however be so great, that the capillary surface is not reached and a rise of the ground-water therefore does not occur. More especially is this likely to be the case after small rainshowers and with a deep-lying capillary surface. In addition to this, by direct evaporation and indirectly through plants, so much water may be drawn off, that an end very quickly comes to the sinking. The explanation of the fact, well-known in practice, that a good shower of rain in periods of drought may be of more importance for the supply of water to the plants than the same amount of water in several small showers, may be in no small measure that the water in the latter case does not sink deeply enough.

In the above no allowance has been made for the occurrence of the non-capillary spaces. In a cultivated soil the uppermost layer, to the depth to which the roots of crops reach and other biological or physical processes make their influence felt, is of a structure in which larger non-capillary spaces, viz., canals and cavities, occur among the capillary cell-system.

In heavy clay soils, beneath the furrow in dry periods, there may occur, besides numerous more or less vertical cracks, also cracks which are mainly horizontal. In consequence of this the breaks between the capillary spaces become so numerous, that it is no longer possible to speak of one capillary cell-system; a great number, as it were, of larger and smaller clods have then been formed. In a soil of this kind the water will in general sink rapidly, and as a result of the presence of these horizontal cracks capillary adjustment from below upwards can no longer take place.

In light clay soils and in sand, however, one capillary cell-system will exist, in spite of the presence of non-capillary spaces; capillary rise is possible in both kinds of soil. Adjustment of water for the crops by means of capillary rise will only be of importance in the light clay soils when a fairly large number of free water-tables of sufficient capacity, evenly distributed, occur. Lateral flow from greater distances is of no importance whatever for the adjustment in these soils. In sandy soils, on the other hand, the capillary rise, besides being under the

influence of flow from free tables, is also under that of an enclosed phreatic surface which is close by and at a higher level.

The presence of canals between the capillary cell-system will cause the amount of water in the capillary zone to be smaller in the case of all soils, but in the light clay soils and sandy soils the capillary rise will not be impeded thereby.

Regarding the way in which the water penetrates into the ground, opinions differ. Lawes, Gilbert and Warington (48) observed with 3 draingauges that very soon after rainfall a fairly large quantity of water could be collected, and then, after a longer time, another smaller quantity. This last quantity, they say, is "discharged from the pores of a saturated soil." The soil during these experiments was in a natural condition, so that there were canals in it; the soil in the three draingauges was 20, 40 and 60 inches thick and was qualified as clay. The water goes, conclude Lawes and his collaborators, through the canals which are due to biological and physical processes, downwards. Leather (49) thinks that this theory is untenable, but that the water for the most part penetrates evenly into the soil and is drawn downwards by means of capillary action and gravitation.

In reality the water will penetrate downwards both through canals and through capillary spaces. But Lawes and his collaborators, on the strength of the tests with the gauges, assumed principally a sinking through the larger spaces, as in their experiments the layers of soil were of no great thickness (respectively 50, 100 and 150 cm.), so that the water sinking through the larger spaces had less time to be absorbed by capillary action. Moreover nothing was growing in the soil in the gauges, so that it was damper, with the result that after rainfall less water could be absorbed by capillary spaces.

Whether under natural conditions the water sinks mainly through canals or through capillary spaces, will depend on:

1. the amount of rainfall. If this, in a particular time, is slight, then it will, after a short time, be absorbed by the capillary action of the walls of the canals, even if the water should at first move downwards mainly through canals. If the rainfall is great, then all the water will finally be able to sink downwards through the canals without being absorbed by capillary action.

2. the texture of the soil. In a coarse soil the water which sinks through canals will penetrate more quickly through the walls of the canals than in a fine soil. Since, moreover, the canals in coarse soil will sooner collapse, the sinking of water will mainly take place in the capillary spaces.

If the water sinking through the canals reaches a free phreatic surface, then it will directly contribute to the rise of the latter, and later on will gradually cause the enclosed phreatic surface to rise; these two rises again will result in capillary rise. This phenomenon will naturally only be speedily perceptible if the phreatic surface is situated at a small depth.

The water sinking through the capillaries forms sejunctions on its way downwards, and is, owing to its low rate of movement, relatively more absorbed by plant-roots. As soon as the capillary surface is reached, this is attended with an immediate rise in the phreatic surface, this rise being as great as that of the capillary surface.

It may thus be said, generally speaking, that the sinking of the water is promoted and the capillary rise is not impeded by the presence of canals.

Finally the cavities in the soil may be considered. Cavities, as stated in the introduction, are to be regarded as non-capillary spaces, which are connected with the atmosphere only by capillary spaces. If cavities are filled with air, they will not become filled with water either when water in the surrounding capillary spaces rises or when it falls. The only possibility of the cavities becoming filled with water is that they should arise from canals which collapse whilst filled with water. If after this a fall of the phreatic surface takes place below the places where the cavities occur, they will remain filled with water as long as they are in the capillary zone. If, however, the capillary zone falls so far that the capillary surface reaches the cavities, water will be withdrawn from the cavities. Therefore cavities filled with water are to be regarded as small water-reservoirs, and they may, as such, assist in supplying the plants with water. The ever-continuing and ever-alternating biological and physiological processes in the upper layers of soil, through which canals arise and disappear again, contribute to this.

Summary

The capillary rise was determined by measurement of the negative capillarity pressure by means of capillarimeters. It was found that the negative capillarity pressure increases with the thickness of the layer of the soil in the capillarimeter and that a maximum is reached with a thickness of at most 20 mm. The capillarity pressure measured with an extremely thin soil layer was accordingly named the minimum negative capillarity pressure, and the one measured with a soil layer of at most 20 mm., the maximum negative capillarity pressure.

It was deduced from this that, in a state of equilibrium above the phreatic surface a capillary zone is possible, in which

- a. practically all the capillary spaces are filled with water;
- b. practically all the capillary spaces in a layer determined by the minimum negative capillarity pressure, are filled with water, whilst above this the number of capillary spaces filled with water gradually decreases.

If the particles of which the soil is composed are all of equal size, then in a — homogeneous — soil of this kind, with the capillarimeters used by the writer, only one negative capillarity pressure can be found; with a homogeneous soil the thickness of the soil layer makes no difference. In the capillary zone of a homogeneous soil all the capillary spaces will be filled with water.

Actually, however, a soil consists of particles of very different sizes, and in a — heterogeneous — soil of this kind the thickness of the layer of soil in the capillarimeter must, as has been demonstrated, necessarily affect the negative capillarity pressure found. The heterogeneity of the soil is, then, the reason why the cases of filling of the capillarity spaces, mentioned under a and b, in the capillary zone may actually occur.

In a state of equilibrium case a is obtained after the sinking of a capillary surface, below which all capillary spaces are filled with water, and after a rise of the capillary surface in a still partly moist soil case b.

The heterogeneity of the soil further renders the filling of all the capillary spaces with water impossible, however the filling has occurred; for this reason the reservations, in cases a and b are mentioned. It may consequently also happen that the maximum water content, after water has risen owing to capillary action in the soil, is not found just above the phreatic surface, but at some distance above it.

The importance of the capillary rise for the supply of water to the crops is as a rule overrated. If, in consequence of a uniform withdrawal of water over a large area, a phreatic surface, which was at first in a state of rest, sinks to the same extent at every point, then adjustment of water by capillary action is of no importance whatever. Such an adjustment will in practice only be of importance in soils with a coarse texture, if a free phreatic surface (a free watertable) of sufficient extent is present; in soils with a fine texture the adjustment is even in that case of little importance, since the capillary action is too slow.

That, notwithstanding this, great value is pretty generally attached to capillary rising, may perhaps result from conclusions having been

drawn from observations made in tubes filled with soil and placed in water. In such cases an appreciable capillary rise must surely take place from a free phreatic surface.

Adjustment of water by funicular action is practically entirely negligible. The greatest quantity of water displaced in sea-sand by funicular action in 33 days was equivalent to $\frac{1}{5}$ mm. rainfall.

From an agricultural point of view it is of interest to know what quantities of water are available for the crops, if no adjustment of water takes place whatever. The uppermost layer of the soil, as far as the roots can develop, is, in consequence of the constant rise and disappearance of cavities and canals, in quite a different condition from the one below. If the air-capacity of the soil at various depths is known, and also the depth at which the phreatic surface lies, then, by determining the negative capillarity pressure (minimum and maximum), an insight may be obtained into the amount of water which may serve as a reserve. By the determination of the absolute water capacity according Kopecky this insight is not obtained.

During the fall of water in capillary spaces, sejunctions are formed as a result of the heterogeneity of the soil. A sejunction is a quantity of water, which is in a state of equilibrium and completely surrounded by a capillary surface. Sejunction water plays an especially important part in the supply of water to the crops in soils with a coarse texture and with a deep-lying phreatic surface.

In a homogeneous soil the capillary rise is inversely proportional to the size of the particles. Microscopic measurements of the soil particles of 5 fractions showed that the maximum negative capillarity pressure is inversely proportional to the dimensions of particles such that the volume of all the smaller particles is $\frac{1}{8}$ of the total volume, and further that the minimum negative capillarity pressure is inversely proportional to the dimensions of particles such that the volume of all the larger particles is $\frac{1}{8}$ of the total volume. It was found at the same time that the dimensions of the particles calculated according to decantation differ widely from the actual dimensions.

The product of the negative capillarity pressure and the size of the corresponding soil particles is constant. The size of this constant was calculated, and with the aid of this the soil may, after the maximum and minimum negative capillarity pressure have been determined, be divided into three fractions.

That a smaller capillary rise was observed in dry soil than in damp soil may also be partly due to the heterogeneity of the soil.

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