THE INFLUENCE OF CLAY PARTICLES ON THE HYDRAULIC CONDUCTIVITY OF SANDY SOILS

M. I. FAHMY

THE INFLUENCE OF CLAY PARTICLES ON THE HYDRAULIC CONDUCTIVITY OF SANDY SOILS

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD
VAN DOCTOR IN DE LANDBOUWKUNDE
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M. I. FAHMY

THEOREMS

I.

There is a quantitative relationship between hydraulic conductivity and granular composition in the deeper layers of marine sandy soils.

"This thesis"

II.

Leaching with diluted sea water is a promising technique in the work of reclaiming sodic soils.

Reeve, R.C. and C. A. Bower. Soil Sci. Aug. 1960

III.

Before non-irrigated reclamation schemes are initiated in subhumid areas with adequate natural drainage, an assessment should be made of the ground water regime after cultivation.

Downes, R.G.
paper presented at a Unesco Symposium on salinity problems in Arid Zones organized jointly with the government of Iran. Teheran, Oct. 1958

IV.

Porosity need not be taken into account in the evaluation of hydraulic conductivity of sandy marine subsoils containing some clay.

"This thesis"

V.

The economic integration of the United Arabic Republic is a successful accomplishment acting as a stimulant for further steps towards economic integration of all the Arab countries.

El Mallagh R. Land Economics, 1960

VI.

It is doubtful whether the "valence-dilution" is an important mechanism in the reclamation of Dutch soils flooded with sea water.

Reeve, R.C. and C. A. Bower. Soil Sci. August 1960

VII.

The problem of obtaining food in sufficient quantities for the increasing world population is frequently somewhat exaggerated. It is likely that the quality of the food which is, or can be made available will prove to be a far more critical factor.

VIII.

An increase of live stock production in Egypt (U.A.R.) could be effected by alterations in some of the prevailing educational systems.

THE INFLUENCE OF CLAY PARTICLES ON THE HYDRAULIC CONDUCTIVITY OF SANDY SOILS

THESIS

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS
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ON FRIDAY 16TH JUNE 1961 AT 16 O'CLOCK

BY

M. I. FAHMY

B. SC. ALEXANDRIA UNIVERSITY, M. SC. CAIRO UNIVERSITY,
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THE INFLUENCE OF CLAY PARTICLES ON THE HYDRAULIC CONDUCTIVITY OF SANDY SOILS

(MET EEN SAMENVATTING IN HET NEDERLANDS)

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KAMPEN, THE NETHERLANDS

(RECEIVED/ONTVANGEN)

CONTENTS

I

INTRODUCTION

For reclamation projects and also for normal agriculture, drainage is a very important subject: wherever the ground water table is naturally high or high by reason of irrigation, successful agriculture is only possible if a drainage system is installed. One of the factors which determines the spacing of such a drainage system is the hydraulic conductivity of the soil; in many formulas the drain-spacing is reckoned as being proportional to the root of the hydraulic conductivity. Accordingly more knowledge about the hydraulic conductivity of agricultural soils is of major interest for the science of land reclamation and improvement. It is the aim of this study to give a contribution to this subject.
The hydraulic conductivity of a soil depends on the number and size of the pores. Two kinds of pores can be distinguished:

1. When the soil particles of which the soil consists are in one-grain structure, the particles do not quite fit together and there are pores left between them (primary pores). The size of these pores will depend on the size of the particles and thus on the texture of the soil. The bigger the particles are, the larger will be the size of the pores and consequently the higher will be the hydraulic conductivity. So in one grain structured soils there is a relation between texture and hydraulic conductivity.

2. However, it is also possible that the particles are in an aggregated form between which secondary pores exist or in other words 'structure pores'. In these soils there does not need to be a correlation between the size of the grains and the size of the pores. On the contrary, the largest structure pores exist mostly in clay soils which consist of very small particles. So in soils with structure pores a correlation between texture and hydraulic conductivity is not to be expected.

For hydraulic problems and especially problems of drainage, the deeper layers which lie under the ground water table, are the most important. In sandy soils, such layers are usually in one grain structure, and it can therefore be expected that a relationship exists between the hydraulic conductivity of those layers and the fineness of the sand. This is important because the evaluation of soil texture is often easier than that of hydraulic conductivity, and it would be very useful in practice, if an estimation of the hydraulic conductivity could be derived from the texture. Because of this, many investigators studied the relationship between the fineness of the sand and its transmission capacity for water. They succeeded to set up formulas by which the hydraulic conductivity could be calculated when the texture is known. These studies dealt mostly with pure sandy soils or with sandy soils with such a low clay content that it is not supposed to influence the hydraulic conductivity.

Up till now, the influence of the clay content on the hydraulic conductivity has not been properly explored, in spite of the fact that most sandy soils contain a certain amount of clay. It is easy to see that the clay content influences the hydraulic conductivity of the soil. The clay particles are deposited in the pores between the sand particles, they block more or less these pores and thus reduce effectively the hydraulic conductivity. Besides depending on the quantity of clay, the magnitude of this reduction will depend on the fineness of the sand, the way the clay particles are distributed in the sand and on the type of clay mineral. It is the aim of this work to study the influence of these clay particles under different circumstances on the hydraulic conductivity of sands.

Hydraulic conductivity measurements are carried out on 'disturbed' and 'undisturbed' samples in the laboratory and by different field methods. The most valuable conductivity measurements are obtained by field methods and those field measurements consequently form a basis against which all other results should be examined. There are, however, a number of reasons for including other methods of conductivity measurements in this study. In the first place field determinations are often more elaborate than laboratory ones. Therefore it is important to investigate if and in which cases laboratory measurements yield the same values for the hydraulic conductivity as field measurements.

A second, and even more important reason for laboratory measurements is that the influence of certain factors, such as the addition of successive increments of clay to sandy soils and the way the clay is distributed in the soil, can be studied the best on artificial samples. For this reason the basis of this research is carried out in the laboratory on artificial mixtures.

In the third place, certain combinations of sand-fineness and clay content are not often met with in the field (at least not in layers sufficiently thick for investigations). As there is a certain correlation between the hydraulic conductivity of artificial mixtures and the hydraulic conductivity of natural soils, it might be possible to use laboratory results to extend the picture obtained from the field determinations and thus to arrive at a general idea of the influence of the clay content on the permeability of sandy soils.

It will appear from this study, that the influence of the clay content will depend, among other things, on the nature of the clay and the way it is distributed in the soil. In different sediments these factors will differ and for that reason the results of this investigation are, strictly speaking, only valid for the sediments with which the investigation took place: the marine sediments of the Zuiderzeepolders in the Netherlands. This does not alter the fact that the results obtained from this research can contribute to a better understanding of the hydraulic conductivity problems of other soils.

I. GENERAL REMARKS ON HYDRAULIC CONDUCTIVITY AND ON THE METHODS FOR ITS DETERMINATION

The movement of water in the soil

Water movement occurs both in saturated and unsaturated soils, but since this study is primarily concerned with problems of drainage, in which saturated layers are naturally the most important, the discussion of the water movement will be confined to such circumstances.

Certain driving forces of various kinds act on soil water: gravitational and adsorptive forces and pressure and osmotic gradient forces. In saturated soils, the osmotic gradient and adsorptive forces normally do not play a rôle in water movement because they either tend to balance each other or the movement of water caused by them is negligible; and it is therefore only necessary to consider the gravitational and pressure gradient forces. In principle, accompanying forces of acceleration and deceleration should also be considered but the velocity of the water movement in the soil is so small that these forces of inertia are relatively insignificant and can be neglected.

The water movement in the soil caused by gravitational force and pressure gradient force can be considered from one point of view by the introduction of the term 'potential'. This is the energy possessed per unit volume in a certain position with reference to the energy of this unit volume at a certain hypothetical level and at atmospheric pressure. If one neglects the adsorptive and the osmotic gradient potentials and the kinetic energy the total potential of a water unit volume will be the net sum of the gravitational and pressure gradient potentials.

The potential energy of a unit volume of water, with the mass ρ, is ρgz where z is the vertical distance to the horizontal reference level. This potential is given in erg/cm^3 in the c.g.s. units. If the pressure in a certain position is p (dynes/cm^2) in the c.g.s. units, then the pressure gradient potential of the unit volume is likewise p, but is now given in erg/cm^3 (dyne/cm^2 = erg/cm^3). The total potential φ is thus:

$$\rho gz + p = \rho g \left(z + \frac{p}{\rho g}\right) = \rho gH$$

where H represents the height of the piezometric level above the reference level.

Soil moisture moves when the total potential in one place is greater than in another. The movement of water depends on the potential gradient in the direction of flow:

$$-\frac{\delta \varphi}{\delta S} = -\rho g \frac{\delta H}{\delta S},$$

where S designates the direction of flow for the point in consideration. $\frac{\delta H}{\delta S}$ is the piezometric gradient which determines the movement of water.

DARCY'S LAW AND THE CONCEPT OF 'CONDUCTIVITY'

The relationship between the water movement in the soil and the piezometric gradient is given by Darcy's law. This law is analogous to that of HAGEN-POISEUILLE which deals with the flow of liquids through capillary tubes. HAGEN (1839) and POISEUILLE (1846) showed that in the case of laminar flow, the quantity of liquid Q, passing through a narrow tube per unit time, is directly proportional to the piezometric or hydraulic gradient (i), the fourth power of the radius of the tube (r), and inversely proportional to the dynamic viscosity of the liquid (η). At the same time, the water density and the acceleration due to gravity are also included in the formula (all terms in the c.g.s. units):

$$Q = \frac{\rho g}{\eta} i \frac{r^4 \pi}{8}$$

In such a capillary tube the discharge is thus proportional to the hydraulic gradient i. Also, in the case of soil pores having cross-sections which are other than circular, the discharge in a laminar flow is proportional to the piezometric gradient. The pores in the soil could be considered as a composite of capillaries of various shapes and cross sections. Therefore, as long as the flow velocities are small enough for the forces of inertia to be negligible, it is to be expected that this proportionality between discharge and piezometric gradient is still valid in the soil; a concept, first stated by DUPUIT (1854). That such a relationship really exists in the soil was experimentally verified by Darcy (1856).

Further, in a homogeneous soil, the discharge is proportional to the cross section of the soil profile. In analogy with Poiseuille's law, the following formula applies to the water movement in soils:

$Q = \frac{\rho g}{\eta} i F$ multiplied by a coefficient which depends on the size, number and shape of the pores, and which thus characterises the pore geometry and obviously represents the term $r^4 \frac{\pi}{8}$ in Poiseuille's law. This coefficient represents the magnitude of the permeability of the soil and is usually designated as K'.

Besides depending on the type of the soil material, the discharge depends (accord ing to this formula) on the density and viscosity of the liquid flowing through it. However, as in soil research the liquid in question is water which shows little temperature variation, the viscosity and the density, and thus the term $\frac{\rho g}{\eta}$ will nearly always have the same value. Therefore, in most cases, this term is not mentioned separately in the formula but is included in the coefficient denoting the properties of the soil porous material; the term $\frac{\rho g}{\eta} K'$ is usually designated as K. Accordingly, the simple formula

$$Q = K i F$$

is reached; the formula originally given by Darcy.

With a unit cross section and with a hydraulic gradient = 1, the proportionality factor is equal to the discharge, so that the factor K is simply called the 'permeability'. This factor thus characterizes the geometry of the porous medium, but in addition to this, it depends on the properties of the liquid involved. At first, this last concept was not clearly understood, because some investigators got the impression that for instance Darcy himself and Slichter (1899), have had in mind this proportionality factor as simply a property of the geometry of the medium. Therefore in the older literature (and also in some of the more recent literature, see chapter III) some confusion may be found regarding this factor. However, this confusion has been brought to an end by the work of RICHARDS (1952) and the 'Subcommittee on permeability and infiltration, Committee in Terminology, Soil Science of America', in which he acted as chairman.

Reasoning by the analogy between OHM's law for the flow of electricity in metals - in which case the proportionality factor is referred to as the electrical conductivity - and DARCY's law, the committee suggested that the ambiguous word permeability should be avoided and that the proportionality factor of DARCY's formula should be termed 'hydraulic conductivity'. The term 'intrinsic permeability' is to be applied to the factor K' which, as mentioned before, refers only to the structure of the porous medium. In this study, the terminology suggested by the committee is adopted and DARCY'S proportionality factor is expressed as 'hydraulic conductivity', often abbreviated to 'conductivity'.

The hydraulic conductivity (K) thus depends on the viscosity and density of the fluid medium, in this case water. Here, the density (with the exceptional case of very saline soils, the problem of which is beyond the scope of this study) is fairly constant, but the viscosity depends to some degree on temperature. However, in the deeper layers of the soil, the temperature assumes a fairly constant character, so that this dependency of viscosity on temperature is not a serious drawback. In the laboratory, however, temperature variations are larger. Because of this, workers in soil research have tended to standardize the hydraulic conductivity to the average soil temperature. In the Netherlands, this average soil temperature is 10°C, and so the values of hy-hydraulic conductivity given in the coming chapters are standardized to this temperature, but in other countries other temperatures may be used. The following table gives a list of the viscosity - to which the hydraulic conductivity is inversely proportional - at different temperatures.

TABLE 1. Viscosity of water for different temperatures

Temperature (in C°)	Dynamic viscosity (in poise)
5	0.015
10	0.013
15	0.011
20	0.010
25	0.009

The values of the intrinsic permeability are usually given in the c.g.s. units. Sometimes these units are also applied to the hydraulic conductivity. In this case the relationship between the two terms takes the expression $K = \frac{\rho g}{\eta} K'$. Apart from the difference of nomenclature, the dimensions of the two terms are also different; K' has the dimension of L^2 and K has that of LT^{-1}.

Values of the hydraulic conductivity, however, are more often given in cm/hour, in inches/hour or in metres/day than in the c.g.s. units, and in this study hydraulic conductivity is given in terms of metres/day. A comparison of the different values is given in the following table:

TABLE 2. Intrinsic permeability and hydraulic conductivity in different units

Hydraulic conductivity at 10° C				Intrinsic permeability
m/d	cm/hr	inch/hr	cm/sec	cm^2
1	4.17	1.64	1.2×10^{-3}	1.5×10^{-8}
0.24	1	0.39	2.8×10^{-4}	3.7×10^{-9}
0.61	2.54	1	7.1×10^{-4}	9.4×10^{-9}
864	3600	1420	1	1.3×10^{-5}
6.5×10^7	2.7×10^8	1.1×10^8	7.5×10^4	1

Briefly summarized the following formula is applied in this study:

Q = K i F where,
Q = discharge in m^3/d,
K = hydraulic conductivity in m/d, standardized to 10° C,
i = piezometric gradient in m/m and
F = cross section of the soil column perpendicular to the direction of flow in m^2.

When the hydraulic conductivity is determined as in Fig. 1, the term Q/F gives the thickness of the water layer, which is discharged in unit time; i.e. the velocity with which the water surface moves during water flow. This coefficient is often called the apparent flow velocity (v in $m^3/m^2/d$). With the introduction of this term (v), the formula becomes

v = K i where,
v = apparent flow velocity in $m^3/m^2/d$,
K = the previously defined hydraulic conductivity in m/d and
i = the piezometric gradient in m/m.

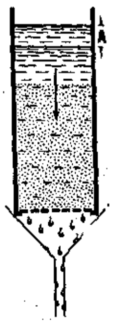

FIG. 1. The apparent flow velocity concept.
A = fall of the water table in unit time
= apparent flow velocity.

The apparent flow velocity is in fact smaller than the actual velocity of the water movement in the soil. In the first place the concept of apparent velocity assumes that the whole cross-section is available for the passage of water, whereas in fact only a part of the cross section of the soil through which the water passes consists of pores, and thus the actual velocity in these pores must indeed be greater than the apparent velocity. In the second place, the water, passing through the pores does not travel directly, but follows a tortuous capillary course, so that the distance covered in a certain time and therefore the velocity must indeed be greater than when the pore system contains straight capillaries, as supposed by the concept of the apparent velocity.

Validity of Darcy's law

Darcy's law thus assumes that the discharge is proportional to the driving force. It is interesting to trace the very much quoted, but obviously rarely read, publication of Darcy and to see the paucity of the experimental data on which he founded his law. This important research work has been carried out on measurements of only 5 sandy samples, using only a few different hydraulic gradients. These hydraulic gradients ranged approximately from 2 to 20, thus, as will be shown in table 3 some of them might have been above the level at which the law can be applied. This might be one of the reasons that his values were far from constant and in fact in the first experiment they ranged from 2.7 to 3.3. Furthermore his data suggest that conductivity may also be decreasing with time, a phenomenon which has caused considerable concern among later workers, including the author.

Nevertheless even from the meagre data of Darcy it is reasonable to deduce the existence of a constant ratio between the discharge and the hydraulic gradient. Later research has confirmed that Darcy's law provides a very accurate picture of the situation, at least up to a certain limit (Rose, 1945). The law even holds for very small hydraulic gradients as 2-3/100,000 (Tolman, 1937).

However, at high velocities Darcy's law is not valid any more because the flow changes from laminar to turbulent. In the soil the validaty even comes to an end at lower velocities than in normal capillaries; either because of accelerating and decelerating forces in the tortuous soil capillaries (Hubburt, 1940), or because these tortuous capillaries promote turbulency (Muskat, 1946). However, both authors agree that when the Reynolds number $R_c = \frac{dv}{\varphi}$ (where v is the apparent flow velocity, d the average particle diameter and φ the kinematic viscosity) is lower than 1, Darcy's law still holds.

According to Darcy's law v is equal to K i and (see chapter III) if it is supposed that

$$K = 47 \times 10^3 \frac{1}{U^2} \text{ and } \frac{1}{U^2} = d^2 \text{ thus } d = 47 \times 10^4 K^{\frac{1}{2}}$$

then it appears that Darcy's law is still valid up to the following hydraulic gradients:

Table 3. Relationship between hydraulic conductivity of soils and hydraulic gradient below which Darcy's law is valid

Hydraulic conductivity (m/d)	Permissible hydraulic gradient for validity Darcy's law
1	2225
10	73
25	19
50	6

These admissible hydraulic gradients are much higher than those found in practice and also higher than those used in the experiments in this study. It is thus clear, that Darcy's law can be applied in the interpretation of the results reported in this thesis.

Factors affecting the hydraulic conductivity of sands

In the following chapters, different factors affecting the hydraulic conductivity will be discussed in some detail. These factors can be briefly summarized as follows:

a. the size of the sand particles,
b. the porosity of the system,
c. the shape of the sand particles,
d. the sorting of the sand,
e. the homogeneity of the system,
f. the clay content and the distribution of the clay particles,
g. the air content of the system and
h. the salt content of the water and the exchangeable cations on the adsorption complex.

As the sand particles are more or less spherical, they do not fit together, and thus the size of the resulting openings depends on the size of the particles. Consequently, the coarser the sand particles, the wider the capillary pore system. According to Poiseuille's law, an increase in the capillary diameter causes considerable increases in the discharge and therefore it is to be expected that a relation exists between the diameter of the sand particles on one hand and the hydraulic conductivity on the other hand. The hydraulic conductivity, however, is not proportional to the fourth power of the pore diameter, as one would suppose from a superficial inspection of Poiseuille's law, as an increase of pore size diameter means a decrease in the number of pores. With the same porosity and the same shape of pores, the number of pores per unit cross section is inversely proportional to the square of their diameter. (Suppose that the separate pores have a square shape with a side length 'a', then the number of pores per cm^2 pore surface will be $1/a^2$. By doubling the diameter of the pores, their number per cm^2 will be $1/4\ a^2$ instead of $1/2\ a^2$). Because of this, the hydraulic conductivity of a sand must be, within the limits of the aforementioned restrictions, proportional to the second power of the pore diameter. In precisely the same way a correlation may be expected between the hydraulic conductivity and the particle diameter.

It also follows from the relationship between Poiseuille's law and that of Darcy, that with the same particle size, the hydraulic conductivity is greater, when the pores between the particles are bigger, or in other words when the porosity is higher (point b).

All sorts of theoretical derivations for the relationship between hydraulic conductivity and particle diameter are based on the assumption that the particles are spherical in shape. In fact, this is not the case, for under the microscope it appears that the sand grains have all kind of shapes and even are often very angular. The particle shape has an influence on the pore shape and consequently an influence on the perimeter-cross section ratio of the pores which is a determining factor for hydraulic conductivity. The particle shape influences also the packing of the sand and thus the porosity of the system and consequently the hydraulic conductivity (point c).

The influence of the sand sorting (point d) on conductivity can easily be seen. When the particles are of different dimensions, the smaller can fit between the bigger; a number of pores is thus blocked, and naturally the conductivity becomes smaller than when all the particles have the same dimensions. The blockage of the bigger pores by the smaller particles can also be indicated by a decrease in porosity.

The smaller particles not only can be distributed homogeneously between the coarser ones, but they also can occur, more or less, in separate layers (point e). This could be the case, in the first place, in artificial samples, when for example they are poured in a permeameter for conductivity determinations, and segregation takes place. More important is the occurrence of fine layers between coarser ones in nature caused by the fact that the sedimentation circumstances, with the course of time, change occasionally and consequently the coarseness of the sedimented material.

The influence of these finer layers on conductivity depends on their relative position with respect to the water flow direction. If the finer layers are completely impervious, this means that with a parallel streaming water, the conducting area is limited; the decrease of discharge and consequently of conductivity is proportional to the (in most cases small) total thickness of these layers. If the flow direction is perpendicular to the finer layers, these supposed impervious layers will entirely block the passage of water, even if there is only one of them. Although the finer layers are rarely totally impervious, yet it appears from this simple consideration that when the fine layers are perpendicular to the streaming water, they have a more detrimental influence on conductivity than when the layers lie parallel to the direction of flow.

With regard to the influence clay particles have on conductivity (point f), one has to consider the fact that they are very fine (average diameter 1000 times smaller than sandy particles), and that in nature (or at least in soils which are not homogeneous) they practically always occur in aggregates (flocs). These aggregates are deposited at the same time with and between the sandy particles. Extremely fine sand particles may be incorporated into these aggregates, but as the clay particles occur in much greater numbers, the character of the system is dominated by them. The pores between the clay particles are so very fine in comparison with those between the sand particles (in the proportion of 1:1000) that in a sandy soil they practically play no role in the movement of water (hydraulic conductivity being, as previously mentioned, proportional to the second power of the pore diameter). Therefore when clay aggregates do exist between a mass of sand, they could be considered as impervious.

These clay flocs are – contrary to the rigid sand particles – very plastic. With sedimentation, their participation in the building up of the porous soil skeleton is very much less than that of the sand particles. When the sedimentation process goes on, they are partly pressed between the underlying sand particles; some of them may have settled already primarily between them. Thus, the clay aggregates block, more or less, the pores between the soil particles and consequently decrease the hydraulic conductivity. The magnitude with which the clay particles decrease the hydraulic conductivity depends on the number of these particles, the way they are aggregated and on the clay type. Montmorillonite has a higher water holding capacity and a greater specific volume than for example illite and consequently possesses a greater blocking capacity relative to its weight.

Clay particles can occur, more or less, in layers between the sand just as in the case of fine and coarse sand layers, the reason again being changes in sedimentation circumstances during the genesis of the soil. When these layers of clay do not contain secondary pores, they are, in comparison with the adjacent sand mass, practically impermeable. So the statements previously made about finer sandy layers situated between coarser masses can be applied with even more force to the case of clay layers between layers of sand. When the clay layers are orientated parallel to the direction of the streaming water, they only limit the available conducting soil volume and their detrimental influence is often not great. If, on the other hand, they lie perpendicular to the water stream, they can practically block the water movement. However, their effect in practice is usually less detrimental; the clay layers are rarely continuous because either they are lying lenticularly between the sand or changing laterally into sand. So the water passage is not totally impeded, but the detrimental effects consist of both the constriction of the available conducting profile + a decrease in the hydraulic gradient because of the longer tortuous way the water has to follow.

Soils, saturated with water, ought not to contain air. When water penetrates a layer of soil, air can be trapped, but as air is lighter than water, it should gradually rise up and vanish from the soil. However, this ascent is impeded by the resistance caused by forces of surface tension. Air occurs as bubbles in the pore system, and the form of these air bubbles is such that they possess the smallest possible surface and surface tension is kept at a minimum. The ascent of the air bubbles via the capillary system necessitates an enlargement of their surfaces. The force needed for this enlargement is often greater than the available bouyancy. Consequently, air finds it difficult to escape totally and so layers, 'saturated with water' can contain air (point g). These air bubbles block the pores, in which they are present and thus reduce water movement and hydraulic conductivity.

Two remaining factors which influence hydraulic conductivity are the exchangeable cations on the adsorption complex of the soil through which water passes and the salt content of the water (point h). In normal cases, calcium is the dominant cation on the adsorption complex. But when the latter contains a considerable amount of sodium, the hydraulic conductivity is greatly decreased probably because sodium-soils are easily peptised. Consequently, clay particles begin to migrate and accumulate in narrow spots in the capillary system where they block the water movement.

Besides the sodium-content of the adsorption complex, the type of salt contained in the streaming water and its concentration also influence conductivity. A high salt concentration will repress the peptisation of the sodium-clay, while the type of salt influences the concentration at which peptisation is prevented. In addition to this the salt content of the streaming water and the type of the salt have an influence on the adsorbed cations and therefore in the long run also influence the conductivity.

The exchangeable cations and the salt content have in particular influence on the clay particles. Pure sandy soils are not influenced by high sodium-content, but in sandy soils with considerable amounts of clay, a high sodium-content can strongly reduce the conductivity. In this research however, the influence of high sodium-content is not studied, as peptisation does not occur in the soils investigated.

METHODS OF DETERMINING THE HYDRAULIC CONDUCTIVITY OF SOILS

Conductivity measurements can be classified in several groups:

- A. Direct measurements (conductivity determined by measuring waterflow)
  - Measurements in the laboratory
    - Measurements in disturbed samples
    - Measurements in undisturbed samples
  - Measurements in the field
    - Measurements in augerholes
    - Measurements from drain-discharge
- B. Indirect measurements (conductivity determined from other data)
  - Calculated from granular composition
  - Calculated from pore size distribution
  - Deduced empirically from granular composition

Hydraulic conductivity determination of disturbed samples in the laboratory

Conductivity determinations of disturbed samples are usually carried out with dried and ground soils. A cylinder (permeameter) is partly filled with the sample and thereafter water is allowed to flow through it. From the hydraulic head, the permeameter cross-section, the length of the soil column and the discharge, the conductivity is easily calculated by using Darcy's law. For practical purposes, in most cases the knowledge of the average conductivity of a big area is required. This means, as conductivity values usually vary from place to place and from one layer to another, that a determination based on one sample is often insufficient, and that more samples have to be taken.

Disturbed samples have the advantage of being easily obtained, transported and filled in in the permeameters. A second advantage is that disturbed samples, when dried and ground are very homogeneous in their pore distribution. Consequently, the conductivity measurements of these samples are more reproducible than those in undisturbed samples which have a more individual pore size distribution and therefore a rather greater variation in conductivity. Thus, dried and ground soils are most suitable for systematic research where the object is to find a relationship between conductivity and other properties (as for example the work carried out by Fireman (1944), studying the influence of salt content on the conductivity of different soils).

On the other hand, the fact that the natural pores are disturbed, is a great disadvantage of this method because it is not certain that the pore system and consequently the conductivity in the disturbed samples will correspond with that in the natural case. And especially the conductivities of natural cores are the point of interest.

In special cases – as for example in sandy soils without secondary pores – the pore distribution and consequently the conductivity of disturbed and undisturbed samples will only show a slight divergence. That this can happen, is evident, for example, from the work of Slater and Byers (1931) who showed that with their samples there was on the whole a good agreement between the conductivity of natural cores and that of disturbed samples of the same soils. However, this is undoubtedly not always the case and the evidence is sometimes conflicting. Thus, Westermann (1909 ref. Sillanpää, 1956) showed that in the soils, investigated by him, undisturbed cores were over 1500 times more permeable than disturbed cores, but McCalla (1944) found higher conductivity rates in disturbed than in undisturbed soils. So for each type of soil it has to be investigated if the two methods agree with each other.

Hydraulic conductivity determination of undisturbed cores in the laboratory

For conductivity investigations of undisturbed cores in the laboratory, cylinders with sharp edges at the bottom are pushed into the soil and then dug out. Thereafter conductivity measurements are carried out in the same way as with disturbed samples. In these undisturbed cores, the natural pore system is still present and therefore it is conceivable that these values of the hydraulic conductivity are more representative for the actual condition in the field.

A disadvantage of this method is that the pore distribution in the field and consequently the conductivity can vary from place to place; so a rather large number of cores is necessary to arrive at a representative conductivity value. Thus, an evaluation of conductivity of a certain area by the undisturbed core method is rather laborious and in addition to this includes the work of transporting the samples to the laboratory and the extra precautions required for the preservation of the natural pore system during this transportation.

This method sometimes has grave drawbacks where macro-pores exist (roots, worm holes or cracks). As long as these macro-pores have only a limited length, measurements of conductivity are not significantly affected, but if the pores cross the soil column from top to bottom, exaggeratedly high conductivity values can frequently be obtained. A well known example for such errors in the Netherlands is found in the research work done on a brackish 'wad' clay. In this soil, the actual clay substance was very impermeable but it contained a number of vertical holes, originating from a reedy vegetation, which had previously grown there. In these measurements – where the cores were obtained by pushing the cylinders vertically in the soil – rather high conductivity values were found which were not confirmed by practical experience when this 'wad' clay was reclaimed.

Hydraulic conductivity determination in the field by the auger hole method

The most simple and rapid method for measuring the hydraulic conductivity of a soil in situ is the auger hole method. This method was introduced by Diserens (1934) and later changed and improved by Hooghoudt (1936), Kirkham and Van Bavel (1949) and Ernst (1950). The determination is carried out by boring a hole into the soil to a depth below the water table. After equilibrium is reached with the surrounding ground water, a part of the water in the hole is withdrawn. As the water seeps again into the hole the rate at which it rises will depend, among other things, on the conductivity of the soil.

Different formulas have been worked out for calculating the conductivity from the velocity of the water uprise and in the Netherlands Ernst's formula is the one usually applied (1950) (see also Van Beers, 1958). This formula, given below, is that used in the case of a homogeneous soil; an impermeable layer at a certain minimum depth ($S \geqslant \frac{1}{2} H$) below the bottom of the auger hole (see fig. 2):

$$K = \frac{4000}{\left(\frac{H}{r} + 20\right)\left(2 - \frac{y}{H}\right)} \cdot \frac{r}{y} \cdot \frac{\Delta y}{\Delta t} \text{ where}$$

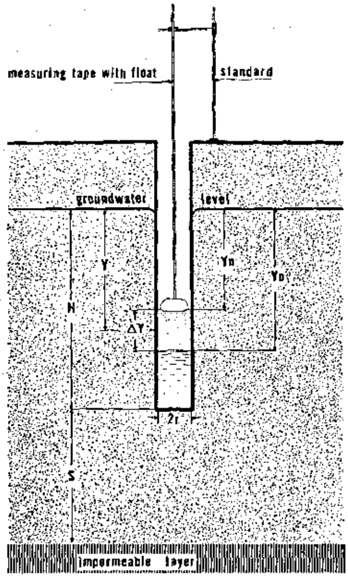

FIG. 2. Diagram indicating the determination of the hydraulic conductivity by the auger hole method.

K = hydraulic conductivity in m/24 hours,
H = depth of hole below the ground water table in cm,
y_0 = distance in cm between the ground water level and the water surface in the hole after removal of water at the time of the first reading,
y_n = the same at the end of the measurement. Usually about 5 readings are taken,
$\Delta y = \Sigma \Delta y_t = y_n - y_0$, the rise of water in the hole during the time of measurement in cm,
y = distance between the groundwater level and the average level of the water in the hole during the time of measurement in cm,

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

r = radius of auger hole in cm and
S = depth of the impermeable layer (or of the layer which has a conductivity of about 1/10 or less of the conductivity of the layers above) below the bottom of the hole in cm.

According to Ernst, values of K have an accuracy of about 20% if the following conditions are met:

$$3 < r < 7, \qquad S > H,$$
$$20 < H < 200, \qquad \frac{\Delta y}{y_o} \leqslant \tfrac{1}{4}.$$
$$\frac{y}{H} > 0.2,$$

The advantage of this method, as already previously mentioned, lies in the fact that measurements of conductivity are carried out in situ. Moreover the measurements, unlike those from undisturbed cores, are representative of a large section, approximately extending between the ground water level and the bottom of the hole. Provided that it remains technically a possibility, this hole can be made as deep as required and may even be extended to cover the whole aquifer. Therefore, the number of measurements needed is not so large as in the case of the undisturbed core method. In addition, this type of measurement reflects the conductivity value for a dominant horizontal flow which is the important one for drainage aspects. One disadvantage of this method is that the conductivity values can only be obtained for layers beneath the ground water table, while in some cases the hydraulic properties of the upper layers are also required.

However, the fact that the conductivity of a large part of the profile can be evaluated turns out to be a disadvantage in this special case, where the relationship between granular composition and conductivity is under investigation. The auger hole method is only suitable for rather thick layers, and to interpret the conductivity found, in terms of granular composition, the soils need to be at least moderately homogeneous. Unfortunately this is rarely the case in marine deposited soils and thus the applicability of the auger hole method for this study is rather restricted.

Hydraulic conductivity measurement in the field by the drain discharge method

Besides the specific methods established for conductivity measurements, it is also possible to estimate conductivity in the field by measuring the discharge of drains. A relationship exists namely between the ground water table midway between the drains and the discharge of these drains and this relationship depends among other things on the conductivity of the soil. The formulas which are given for this relationship were originally developed for another purpose, namely to find out the proper spacing of the drains when the soil conductivity is known. However, where drains already have been installed these formulas can be used also in estimating conductivity.

As the flow of water to a drain is a very complicated process, some simplifications are usually introduced when the relation between discharge, groundwatertable and conductivity is sought. Several formulas exist depending on the different assumptions made, such as those of Hooghoudt (1940) and Van Deemter (1950). In Hooghoudt's equation, which is usually applied in this type of work in the Netherlands, one of the assumptions made is that an impermeable layer exists in the profile at a certain depth beneath which the flow of water does not take place. Another assumption made in the formula is that a state of permanent flow exists which means that the outflow equals the inflow; this point will be discussed in a later chapter. For other assumptions, made in the deriviation of the formula, see Hooghoudt (1940).

The equation in its most complete form runs as follows (see fig. 3):

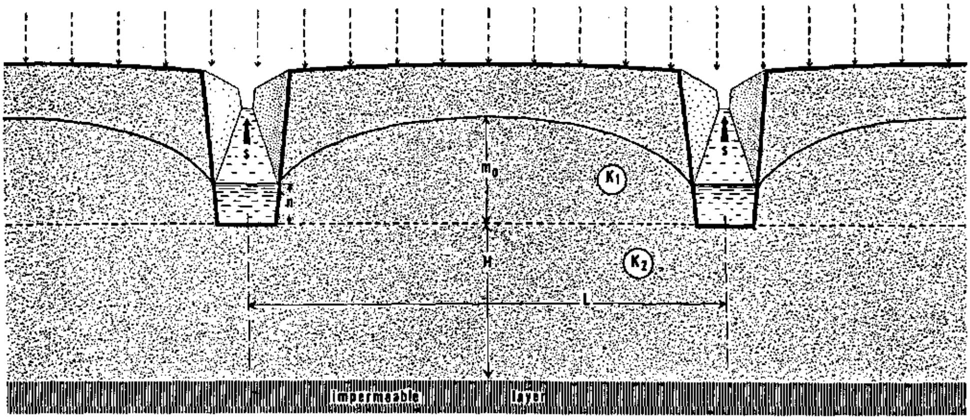

FIG. 3. Diagram indicating the determination of the hydraulic conductivity by the drain discharge method (the open drains in perspective).

$$S = \frac{8\,K_2\,d\,(m_0 - n) + 4\,K_1\,(m_0 + n)\,(m_0 - n)}{L^2} \quad \text{where,}$$

S = the discharge of water expressed in m/d,
K_2 = the average hydraulic conductivity of the strata lying between the tile drain level (or bottom of the ditch level) and the impermeable layer in the subsoil in m/d,
m_0 = the height of the water table midway between the tile drains or the ditches above the level of the tile drains (or the bottom of the ditches) in m,
n = the height of the water table above the tile drains (or in the ditches) in m,
K_1 = the hydraulic conductivity of the soil above the tile drains (or the bottom of the ditches) in m/d,
L = the distance between the tile drains or ditches in m,
H = the depth of the impermeable layer below the level of the tile drains (or the bottom of the ditches) in m and
d = an equivalent depth, derived from H in which allowance is made for the radial resistance and by which the assumption of the horizontal flow (a fundamental assumption of the above formula) can be maintained.

The ratio d/H depends on the diameter of the drains and the distance between them. An example of this relationship is shown in table 4 where values of d, are given for a tile drain having a diameter of 12 cm and for different values of H and L. Further details may be found in the relevant literature (HOOGHOUDT, 1940).

TABLE 4. Thickness of d (= equivalent layer) at different values of H (distance between the level of the drains and the impermeable layer) and L (drain spacing) with a tile drain diameter of 12 cm (HOOGHOUDT 1940)

H in m	Drain distance in m			
	20	50	100	200
2	1.3	1.6	1.8	1.9
5	1.7	2.8	3.6	4.2
10	1.7	3.4	5.1	6.8
20	1.7	3.5	6.1	9.4
50	1.7	3.5	6.3	11.3

It appears from the table that the greater the ratio of the distance between the drains (L) to the depth of the actual impermeable layer (H), the smaller is the difference between H and d.

The advantages and disadvantages of this method can easily be seen: no other method of determining conductivity is more closely connected with its most important application in practice – that of estimating drain spacings. Furthermore, conductivity values obtained in this way, represent a large area and the whole depth of the profile in which water movement takes place.

On the other hand, when a land is not yet drained and the conductivity has to be determined, then it is obvious that the method cannot be applied. In the present investigation, one of the major disadvantages encountered, and one which applies to this method even more than in the case of the auger hole method, is that the values obtained represent the average conductivity of a considerable volume of soil. Such a volume is rarely homogeneous and it is therefore difficult to relate conductivity measurements made in this way to granular composition. Only in exceptional cases is a large section in the field homogeneous in its granular composition.

APPLICABILITY OF THE DIFFERENT METHODS OF HYDRAULIC CONDUCTIVITY MEASUREMENTS FOR THIS RESEARCH

From this survey of different methods of conductivity measurements, it can be concluded that for present purposes, where the aim is to study the influence of the clay content on the conductivity of sands of different fineness, no one method is altogether suitable. When a method is more closely linked to the circumstances in the field, and thus probably gives a better picture of the conductivity there, its application is usually limited to specific cases.

Certain combinations of fineness of sand and clay content can be investigated only with methods which correspond less closely to natural circumstances, but in order to get a more complete picture of the influence of the clay content on the conductivity it is necessary to use also methods which are less closely linked to the circumstances in the field. Thereafter the results of these methods must be interpreted in the light of those cases in which a comparison with methods which correspond more closely with the practical circumstances, is indeed possible.

In the present study, the determinations of the conductivity of disturbed samples were of particular importance as only in disturbed samples the granular composition could be varied as required and subjected to systematic research. For this reason, the work of artificial mixtures of sand and clay formed an integral part of this study.

Calculation of hydraulic conductivity from the granular composition

The conductivity of a sandy soil depends on the number and size of the pores which in their turn, if the soil does not contain secondary pores, depend on the particle size of the sand. Thus, for soils with only primary pores, a relationship between the particle size of the sand and conductivity should exist. Several investigators have occupied themselves with calculations of this relationship and an appraisal of some of their formulas is made in a later chapter. The principle of the method is best illustrated by the Kozeny/Carman formula (1939) and due to its importance, the full derivation is shown below.

The formula is derived from Poiseuille's law for cylindrical tubes (all terms in the c.g.s. units):

$$v' = \frac{g\, d^2\, \rho}{32} \; \frac{\Delta p}{\eta L} \qquad \text{where} \qquad (1)$$

v' = velocity of the water,
g = acceleration due to gravity,
ρ = water density,
d = diameter of the tube,
Δp = hydraulic head,
L = length of the tube and
η = dynamic water viscosity.

When the diameter d is replaced by the hydraulic radius m, which is $\frac{\text{volume of the tube}}{\text{area of the wetted surface}}$,

$$m = \frac{\pi}{4} d^2 L : \pi d L = \frac{d}{4}, \text{ and } d^2 = 16\, m^2$$

Then, by substitution, formula (1) becomes

$$v' = \frac{g\, m^2\, \rho}{2} \; \frac{\Delta p}{\eta\, L} \qquad (2)$$

The factor 2 in this formula can be considered as representing the relationship between the hydraulic radius and the form of the tube in capillary flow for a cylindrical tube. This factor varies with different shapes of tube from about 1.8 to 3.0. Kozeny/

Carman assumed a value of about 2.5 for the pores in the soil. The formula now is:

$$v' = \frac{g\, m^2\, \rho}{2.5} \quad \frac{\Delta p}{\eta\, L} \tag{3}$$

When the formula is to be applied to the soil, one has to consider the fact that the pores in the soil are channels of a rather involved shape, but that with complete random arrangement the pore system is statistically the same for every cross section of a certain soil. However the path of the water in this statistically constant pore system is tortuous and thus must be longer than L; the actual length should be L_e. Further, when one shifts from a capillary tube to the condition in the soil whereby the velocity is defined as the apparent flow velocity (= v), the actual velocity of the water (v′) is greater than this apparent velocity, because only a part of the total cross section (the porous part, given the term ε) is available for the water transmission. The actual velocity of the water is thus $v \cdot \frac{1}{\varepsilon} \cdot \frac{L_e}{L}$.

With these considerations equation (3) takes the forms

$$\frac{v}{\varepsilon} \cdot \frac{L_e}{L} = \frac{g\, m^2\, \rho}{2.5} \cdot \frac{\Delta p}{\eta\, L_e}$$

multiplying the numerator and denominator by L,

$$v = \frac{\varepsilon\, m^2\, \rho}{2.5} \cdot \frac{\Delta p g}{\eta\, L} \cdot \left(\frac{L}{L_e}\right)^2 \tag{4}$$

According to Darcy's law, for the unit of cross section

$$v = \frac{\rho\, g}{\eta}\, K' \frac{\Delta p}{L},$$

in which K′ = the intrinsic permeability, thus

$$\frac{\rho\, g\, K'}{\eta} \cdot \frac{\Delta p}{L} = \frac{\varepsilon\, m^2\, \rho}{2.5} \cdot \frac{\Delta p g}{\eta\, L} \left(\frac{L}{L_e}\right)^2, \text{ or } K' = \frac{\varepsilon\, m^2}{2.5} \cdot \left(\frac{L}{L_e}\right)^2 \tag{5}$$

Kozeny/Carman assumed that the actual length which the water has to path $L_e = \sqrt{2} \cdot L$. Equation (5) becomes then

$$K' = \frac{\varepsilon\, m^2}{5} \tag{6}$$

The term $m = \frac{\text{volume of the pore system}}{\text{wetted area of the pore system}} = \frac{\varepsilon}{S}$ where S is the surface of the soil particles per unit volume. Substituting, the equation is rendered.

$$K' = \frac{\varepsilon^3}{5\, S^2} \tag{7}$$

As the porous part of the soil is ε, the soil particle volume per unit (sand + pore) volume $= 1 - \varepsilon$. The surface of the soil particles per unit volume soil particles (without the pores) $= S_0 = \frac{S}{1 - \varepsilon}$. Equation (7) now takes the form

$$K' = \frac{1}{5\, S_0^2} \cdot \frac{\varepsilon^3}{(1 - \varepsilon)^2} \qquad (8)$$

According to ZUNKER (1921) the following expression applies to sheprical grains:

$$S_0 = 6\, U$$

where U isthe specific surface of the sand, with grains of 1 cm diameter as base (see also page 22). Formula 8 now becomes:

$$K' = \frac{1}{180\, U^2} \cdot \frac{\varepsilon^3}{(1 - \varepsilon)^2} \qquad (9)$$

In this formula the 'permeability' is expressed as intrinsic permeability. Expressed as hydraulic conductivity the formula becomes:

$$K = 360 \times 10^3 \frac{\varepsilon^3}{(1 - \varepsilon)^2} \cdot \frac{1}{U^2}$$

This formula indicates that the conductivity can be calculated from the specific surface of the sand and the porosity. The specific surface can be calculated from the granulometric analysis (see page 23).

The advantages and disadvantages of this method in estimating conductivity will be discussed in a separate section. Here it will suffice to mention a methodical drawback; i.e. the calculation of the conductivity is based on assumptions which are certainly not completely right. For that reason the reliability of this method has to be tested before it can be applied; in the first place for pure sands but over and above that in cases when clay particles also occur.

CALCULATION OF HYDRAULIC CONDUCTIVITY FROM THE PORE SIZE DISTRIBUTION

The pore size distribution can also be calculated from the pF curve, using the equation

$$r = 2\, \delta / \rho\, g\, h$$

where δ and ρ are respectively the surface tension and the density of water and g the acceleration due to gravity. The symbol r corresponds to the upper limiting radius of pores which are still holding water when a suction of h is applied to the water in wet soil. When applying a greater suction pressure, the volume of water withdrawn (between the two pressures) will represent the volume of pores with radii lying between the two values calculated from the previous equation. The pore size distribution can be thus determined directly from the water content – suction curve for porous mediums. By using one of the formulas given either by CHILDS and COLLIS-GEORGE (1950) or MARSHALL (1958), which relate the permeability to the pore size distribution, the conductivity can be calculated.

An advantage of this method is that the measurements can be carried out with undisturbed cores so that it is also possible to make allowance for the effects of secondary pores. The disadvantage of the method lies in the long time of its duration, longer than a direct conductivity measurement which remains of course preferable. Thus the method has a very limited practical value.

THE IMPORTANCE OF THE RELATIONSHIP BETWEEN GRANULAR COMPOSITION AND HYDRAULIC CONDUCTIVITY

It has already been mentioned in a previous paragraph, that a relationship exists between the granular composition of a sand and its conductivity. On this relationship clay particles have an influence due to their presence in the pore space between the sand grains. The clay particles block a part of the pores and consequently reduce the conductivity.

For several reasons it is important to determine this relationship between the granular composition of sand and its conductivity and to determine to what extent increasing amounts of clay affect the conductivity of sand in the different textures. In the first place because the measurement of the granular composition in soil laboratories and institutes is a routine analysis and thus, if the above mentioned relationship is known, conductivities could often be estimated from data which are already available. Furthermore the granular composition holds an important place in mapping and describing fluviatile and marine sediments because it has a bearing on their genesis and physiography. So if such an area has been surveyed and mapped, data obtained from the sandy layers could be interpreted in terms of conductivity. It is also a fact that the granular composition of sand (clay content and fineness) can be fairly well guessed by the hand. Consequently it would be also possible to make a rough estimate of the conductivity in the field.

Naturally the relationship between conductivity and granular composition hold only for sandy soils without secondary pores, but fortunately, the majority of the deeper layers of marine and fluviatile sands are of this type.

II. METHODS OF INVESTIGATION

It appeared from the last chapter that conductivity determinations can be carried out in a number of different ways; several of this methods are employed in this study. It is necessary to discuss in some detail the methods used, to show the difficulties encountered and the way they have been tackled. As these considerations and investigations are only of methodical importance, anyone who is only interested in the practical results can avoid reading this chapter.

Every method has its own difficulties and drawbacks and the longer a method is established the more is known about its advantages and disadvantages. Conductivity measurements carried out by the auger hole- and the drain discharge method have been put in use rather recently and as a consequence of this, not much is known about their drawbacks and methodical difficulties. Laboratory investigation of sample took place, however, since a very long time and workers through their accumulated experiences, learned to be aware of a great number of faults and difficulties which might take place. As a result, it will appear from hereon that the discussionsof the laboratory determinations are rather long and those of the field are rather short.

THE DETERMINATION OF THE GRANULAR COMPOSITION

It is the aim of this study to investigate the relationship between granular composition and hydraulic conductivity of sandy soils. Thus some remarks have to be made about the determination of the granular composition. This granular composition was determined by the method of the INTERNATIONAL SOCIETY OF SOIL SCIENCE (1929). The soil was treated with hydrogen peroxide in order to destroy the organic matter and then boiled with dilute hydrochloric acid to get rid of the calcium carbonate. The excess of hydrochloric acid and the soluble salts formed were removed by repeated decantations. The clay was peptised with a peptising agent (in this case pyrophosphate) and then the amounts of clay and silt in the suspension were determined by the pipette method.

The sand composition was determined by rinsing the peptised samples in Atterberg cylinders after which the clay and silt fractions were removed by repeated decantations. After drying, the remaining sand was separated into different grades of fineness by sieving through a set of 10 sieves. The sizes of the meshes of these sieves are standardized and the ratio between successive sizes is $1:\sqrt{2}$; only the finest subfraction has a greater range (16-50 mu).

In studying the relationship between granular composition and conductivity it is difficult to know how to deal with the 10 figures, resulting from the analysis of the sand. It is necessary to calculate from them one meaningful figure, which has a bearing on the conductivity. This can be done in several different ways but in the Netherlands the so-called specific surface (U), originated by Zunker, is used. This is an expression indicating the ratio between the total surface of all particles and the surface of an equal quantity by weight of particles of the same material with a diameter of 1 cm, with the assumption of the sphericity of the particles. When the sand particles are smaller, the surface is bigger in proportion to the weight and thus the U figure is a parameter for the particle size.

In calculating the U figure of a certain subfraction, it is assumed that the particles are evenly distributed between the sizes of the two sieve meshes and that they are spherical in shape. In this case the formula for the calculation is:

$$U_{cm} = \frac{0.4343}{\log d_1 - \log d_2} \left(\frac{1}{d_2} - \frac{1}{d_1}\right)$$

where d_1 is the biggest and d_2 is the smallest diameter of the subfraction under consideration. Log d_1 and log d_2 are the Briggsian logarithms of the diameter particles. The U figure obtained of each fraction of the sand is then multiplied by the weight of the fraction and the sum of all these products is divided by the total weight of the subfractions of the sand to give the value of U for the sand as a whole.

Such calculations seem to be rather lengthy, but when the same sieves are used, then the U figure for a given fraction is always the same and thus the calculation simply consists of the appropriate multiplications, summations and divisions. In the Netherlands the determination of the U figure is a normal routine analysis used in classifying sandy soils.

In marine sand sediments near and below the ground water table the organic matter is closely related to the clay content; the former amounts to about 10% of the latter. A constant relationship also exists between the quantities of clay (0–2 μ) and silt (2–16 μ), the clay content being approximately double that of the silt (ZUUR, 1954)[1]. Thus when the influence of clay content on conductivity is discussed this includes the influence of the silt and of small quantities of organic matter.

The soils under investigation contained calcium carbonate (0–10%). This calcium carbonate is removed during the determination of the granular composition though it contributes to the granular composition and thus affects the conductivity. This, however, is not a serious drawback because the calcium carbonate content of the investigated samples was not exceptionally high (0–10%). Moreover all subfractions contain calcium carbonate. Although its content might be higher in the finer fractions than in the coarser ones, the resulting error is small so that the U figure is about the same whether or not the calcium carbonate was involved in the determinations.

THE APPARATUS USED FOR THE DETERMINATION OF THE HYDRAULIC CONDUCTIVITY OF DISTURBED SAMPLES IN THE LABORATORY

Conductivity measurements in the laboratory are carried out (as already mentioned in the previous chapter) in cylinders filled with soil through which water is allowed to flow. This can be done in two different ways: In the first case a certain amount of

[1] Some of the soils discussed in chapter IV contain relatively bigger quantities of silt but as the total quantity was still very small this deviation was not sufficiently great to merit attention.

water is poured on the soil and allowed to percolate through it naturally, but this means that the hydraulic gradient is not kept constant. In the second case, the hydraulic gradient is kept constant by replenishing the source of the percolating water. According to ANDERSSON (1953) the first method is more suitable for soils having low hydraulic conductivities and the second for more permeable soils. Because most of the samples investigated in this study were rather permeable, the method with the constant hydraulic head was favoured. Moreover, this system is more suitable for carrying out series of determinations.

Another difference is the direction of the percolating water which can be allowed to travel from top to bottom or vice versa. The disadvantage of the former is that desintigration of the structure of the upper layer can easily take place; this difficulty will be dealt with more fully later on. The latter method, which has the advantage of needing only a relatively simple apparatus is also not without difficulties. Thus if an upward hydraulic head is applied to the sample, the seepage force (which equals the bouyancy ρ g i) may exceed the submerged weight of the soil particles and the sample starts boiling (Taylor, 1948). It was therefore necessary in this investigation, where determinations were made with an upward flow of water, to use a low hydraulic head.

The principle of the apparatus is shown in fig. 4. The type is about the same as has been developed by ERNST and his coworker WIT at the 'Instituut voor Cultuurtechniek en Waterhuishouding Wageningen'. One of the main parts of this apparatus was the container A, made from transparant plastic with dimensions 90 x 17.5 x 29 cm. This container was filled with water up to a certain level and the permeameters were then placed in it. Originally it was intended that the water should be kept at a constant level by connecting the container with a Mariotte-system. It appeared, however, that this system did not give so constant a level, as was necessary for the low hydraulic head being used. It was thus necessary to install a buffer tank between the Mariotte system and the container. The Mariotte system delivered the water to the buffer tank and this buffer tank discharged the water to the container by a regulating tap (1 in fig. 4). The excess water in the container ran out through a movable outlet (8) that could be raised or lowered according to the required hydraulic head.

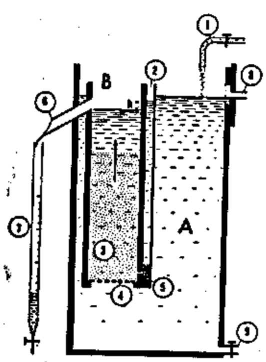

FIG. 4. Apparatus used for the determination of the hydraulic conductivity of disturbed samples in the laboratory.

A permeameter container
B. permeameter
1. liquid outlet from Mariotte system
2. manometer
3. soil
4. filter
5. glass wool
6. permeameter outlet
7. burette
8. changeable liquid outlet to waste
9. liquid outlet to waste.

In the container a series of 10 permeameters (B) could be mounted. These permeameters were cylindrical and also constructed of transparent plastic for reasons which are mentioned later. The diameter of such a permeameter was 6 cm and the length 21 cm. The bottom of the cylinder which could be screwed on so that it fitted tightly, consisted of two plastic plates closely fitting into each other and perforated with small holes of 2 mm diameter. A piece of nylon cloth was placed between the two plates and another in top of it. It appeared from experiments that the hydraulic resistance of these bottoms + nylon clothes can be neglected. The permeameter was suspended from the side of the container by its plastic outlet tube. Leakage between the tube and the wall was prevented by a rubber ring.

After the permeameters were filled with soil, they were placed in the container where the level of the water was kept higher than the level in the permeameter. This water flows out of the container from base to top of the permeameter (see fig. 4). The effective hydraulic head for the water movement is the height h in fig. 4 (see also page 31). The discharged water was received and measured in a burette attached to the container.

An electro-micrometric apparatus (not shown in the fig.) was moved about over the tank on two strongly fixed bars, thus enabling the hydraulic heads of the whole series of permeameters to be measured. The accuracy of the micrometer measurement was one tenth of a millimeter. Before every set of measurements was carried out, the electric micrometer was adjusted to 0 (for the free water surface).

With this apparatus, the quantity of the discharged water from the permeameter in a certain time was measured with the corresponding hydraulic head. In calculating conductivity, it is also necessary to know the length of the soil column, the permeameter cross section and the water temperature. The equation for the calculation of the hydraulic conductivity is:

$$K = 864 \cdot \frac{L}{h} \cdot \frac{Q}{F} \cdot \frac{\eta_t}{\eta_{10^\circ c}} \cdot \quad \text{where,}$$

K = hydraulic conductivity in m/24 hours,
L = length of soil column in cm,
h = hydraulic head in cm,
Q = discharge in cm^3/sec.,
F = permeameter cross section in cm^2,
η_t = viscosity of the used water in poises and
$\eta_{10^\circ c}$ = viscosity of water at 10° C in poises.

It can thus be seen that in principle this type of measurement of conductivity in disturbed samples in the laboratory is fairly simple. However, in practice, certain difficulties have been encountered which are discussed under the following headings.

The filling of the permeameter

When a permeameter is packed with air-dried soil, segregation of the components into fine and coarse layers can easily take place. Should this segregation occur, it would have a detrimental effect on conductivity (see page 14). This is the reason that transparent permeameters are used. Thus lack of homogeneity of the soil column can be seen and steps can be taken to prevent it by filling in a proper way. Further, the way in which the permeameter is filled is important because it also influences the porosity of the sample which in its turn affects the conductivity. To have reproducible results and reliable interpretations of the figures obtained, the packing of the permeameter should always be carried out in the same manner. Thus in packing a permeameter the principal requirements are that there should be a standardised method of filling which also gives a homogeneous sample.

Various methods have been proposed by different investigators to satisfy these requirements. Chu *et al* (1954) applied the inverted tube method where the permeameter is set upside down and the sample is introduced in stages through a funnel. Henin (1958) chose a method in which samples are gradually poured in, in such a way that they are always covered by a layer of water. He states that the method is effective in preventing segregation. Reeve and Brooks (1953) produced an equipment with which the sample is thoroughly mixed in an above compartment and then dumped in the permeameter. Fireman (1944), after trying several different methods for obtaining uniformity of packing found that the most suitable method was to drop the soil filled permeameter repeatedly upon a solid wooden block.

In this study many attempts have been made to arrive at a satisfactory method of packing disturbed samples. The one which gave the best results was as follows: a 500 gram 2 mm-sieved sample is thoroughly mixed and dumped on a wide open-mouthed funnel with a long stem which is closed at the bottom by the finger. The stem of the funnel is then inserted in the permeameter and the sample is allowed to settle by removing the finger. The stem is raised slowly with the precaution that its bottom should always touch the upper surface of the soil in the permeameter. During this procedure the parts of the sample in the funnel and in the permeameter are continuously stirred with a metal rod. As the permeameter is filled with the sample, it is allowed to drop 100 times from a height of about 2.5 cm onto a wooden block.

Different samples of sand and mixtures of sand and clay were so treated and the homogeneity and reproducibility of porosity were found to be satisfactory. The former was ascertained by examining the samples through the transparent walls of the permeameter where it could be seen that the degree of homogeneity was good and that there was practically no segregation. The reproducibility of porosities is shown in table 5, containing the results of 5 replicates of sands with different U figures and different percentages of added clay (for an explanation of the term "U figure" see page 22). The porosity was calculated from the length of the soil column, the cross sectional area, and the oven dried weight of the sample, assuming a specific weight of the soil of 2.65.

TABLE 5. Reproducibility of porosity determined in some sands and artificial mixtures of sand and clay.

U figure of sand and % clay	Porosity of replicates (as part of total volume)				
	1	2	3	4	5
43– 0	0.33	0.33	0.33	0.35	0.33
43– 5	0.39	0.39	0.40	0.39	0.39
120–10	0.46	0.46	0.46	0.46	0.47
170– 0	0.38	0.39	0.39	0.39	0.39
170–10	0.46	0.46	0.46	0.46	0.46

DISPERSION AND MICROEROSION

In disturbed samples, measurements of long duration show a decreased conductivity with time, a phenomenon which will be discussed in more detail later. Several different explanations of this occurrence have been advanced; one of which is that soils containing clay disperse with time. The dispersed clay migrates with the flow of water and settles in very narrow pores. This leads to blockage of these pores and decrease of conductivity.

The dispersion and erosion may be caused in two ways, one chemical, the other physical. The chemical runs as follows: The soil solution has a certain salt content which causes the flocculation of the clay. When the percolating water, used in the measurements, contains a lower salt content, the soil solution changes and consequently the clay may be peptised and transported. As for the physical cause, when the percolating water happens to have a velocity greater than that occurring in nature, erosion of the clay aggregates and clay transportation may take place. As not much work has been done on dispersion and microerosion, it is unknown if they are of much importance during permeability measurements. But in any case there was naturally every reason to take precautions to prevent such phenomena. To prevent peptisation the samples were not percolated with pure water but with a 0.004 n $CaCl_2$ solution. This concentration is higher than that assumed by QUIRK AND SCHOFIELD (1955) as being the threshold limit (0.00015 n $CaCl_2$) below which conductivity decreases as a result of dispersion.

For preventing microerosion, in the first place, the samples were percolated in an upward direction as previously mentioned. If the water streams in a downward direction, turbulence can easily occur in the water layer on the surface. This can lead to a whirling up of the clay particles which later on can be deposited on the soil surface as an impermeable film. The second measure to prevent erosion was to keep the hydraulic gradient as low as was technically possible; as the hydraulic heads used were about 1.5 cm and the soil column lengths were about 10 cm, the hydraulic gradients were about 0.15.

Entrapment of air and pretreatment of the samples

As already has been mentioned in the introduction the so-called water saturated samples still can contain air bubbles. These air bubbles are very resistant and they cause a decrease in conductivity. Since in nature soils below the ground water table have a low air content, it is necessary to deminish the air content of the samples in laboratory determinations so far as possible.

The air content in the soil comes from two sources: firstly air which is present in the presaturated soil and secondly air which evolves from the water percolating the soil. This evolution happens when the water used is oversaturated with air, either as a result of its prehistory or because the laboratory temperature is higher than the original water temperature; this air is inclined to evolve on angular objects.

During the saturation of an air dried soil, the water advances very irregularly in the column and so great quantities of air can be easily entrapped. Several methods of saturating the samples have been studied by such workers as Slater and Byers (1931), Zimmerman (1936) and Christiansen (1944). It appears, however, from these studies that some air is always entrapped whether water is introduced from above, from below or under a head.

The only two ways of fully saturating the soil are either by evacuating the air prior to saturation or by replacing it by CO_2 (which then dissolves easily in the streaming water) (Christiansen, 1944 and Christiansen et al. 1946). Saturation after evacuation was found by Christiansen to cause breakdown of structure and to result in a much lower conductivity than when the soil is wetted in the normal manner.

Replacement of soil air by CO_2 is rather time consuming, while structure breakdown of the samples investigated in this study (sands, artificial mixtures of sands and clay or undisturbed sandy samples from the subsoil, which are considered to be more or less structureless) is not likely to be a serious matter. Therefore, in this study the samples were evacuated before saturation.

The method is to place permeameters with the packed samples in desiccators and then to apply suction. After some minutes, during which time most of the air is removed from the desiccator, water is introduced by opening a valve very slowly, and the water penetrates the soil from beneath. The time required for saturating the samples ranges from 1 to 3 hours according to the fineness of the sand and the clay content.

Some preliminary trials showed that with some samples, especially those containing clay, distortion took place as the water front advanced in the soil columns. It seems possible that some air is however left in the soil, and as the water penetrates the soil column, this air is compressed and this leads to the uplifting of the soil. A perforated plastic disc was therefore placed on the top of the sample. This disc had 3 short stems which allow for supporting an aluminium weight of one kilogram. This proved to be efficient in preventing the previous mentioned phenomenon.

After saturation, the permeameter was removed from the desiccator and allowed to drop 50 times by a standarized procedure. This was done to ensure restoration of the initial porosity if it had been altered during suction and saturation. Immediately after this, the permeameters were put in the container full of water and the measurement of the conductivity was made.

Besides the air which was already in the sample, it is still necessary to deal with the air which evolves from the water percolating the soil. The best way to prevent this evolution is to use boiled water which is totally air-free. However, since this would be very laborious work, hot water (70–80° C) from a boiler was used. This water was then stored in 10 *l* bottles and left to cool overnight to 18–20° C. It was expected that in this way most of the air in the water would be eliminated. It appears, however, from experiments described later that it is doubtful whether this assumption is right. Perhaps the water in the container, in which the permeameters were placed, adsorbed also a new air. The volume of the container was large compared with the quantity of water used for a series of determinations; consequently the water in the container was only slowly renewed and had ample time to adsorb air. In any case bubbles were seen more than once through the walls of the container.

Fluctuations of hydraulic conductivity with time

Many investigators have pointed out that conductivity measurements in permeameters are not constant with time. The type of the soil probably plays a role in the processes which lead to these changes and probably different investigators have not used the same type.

Christiansen (1944), Fireman and Bodman (1939), Allison (1947) and others showed that if the percolation of water through the permeameters takes place over several weeks or months, three distinct phases can be recognized:

1. An initial period where the conductivity decreases, sometimes slightly but usually to a small fraction of the original rate,
2. A second phase where conductivity increases,
3. A third phase where the conductivity again decreases, but now gradually and steadily during the remainder of the test.

This behaviour is attributed by most investigators to the following factors: The decrease of conductivity in the first phase is caused by the swelling of clay and the dispersion of the soil as the electrolytes are leached by the percolating water. In the second phase, the increase of hydraulic conductivity is attributed to the gradual solution of entrapped air from the soil by the percolating water. The gradual decrease of the third phase is supposed to be due to the clogging of soil pores by microbiological products according to Allison (1947), to rearrangement of clay particles according to Bodman and Harradine (1938), and to the migration and accumulation of fine soil material (a kind of microerosion) according to Sillanpää (1956).

It seems that differences in the shape of the conductivity curves are due to differences in methods of presaturation and the kind of water used. If, for example, the air is taken out by wetting the soil under vacuum, Christiansen (1944) and Sillanpää (1956) found that conductivity is at maximum in the beginning of the test and decreases gradually. Thus, the second phase in which the conductivity increases is absent.

This variation in conductivity is a great inconvenience in conductivity research. Firstly, the values obtained will depend on the time at which the measurements are made and it is unknown at which time the records represent the natural circumstan- ces. Further, where different samples are to be compared, it is questionable whether measurements made after a standard period of time will be at the same phase in the conductivity curve because this curve depends on the type of soil.

That is why several investigators are inclined to measure the conductivity in the third phase when it is approximately constant (Sillanpää, 1956). The time at which the third phase is reached will depend, however, on the magnitude of swelling and dis- persion, on the quantity of air left in the samples after saturation and on the rate of its removal which will again depend on the type of the soil under study. It is no won- der then that the time given by several investigators for reaching this third phase or in any case for recording the conductivity measurements varies so much; Arronovici and Donnan (1946) 100–400 hours, Amer (1960) 72 hours, Reeve (1953) 85 hours and Mc Intyre (1958) 1 to 2 hours.

Apart from the problem of determining the moment at which the third phase begins, the value of the measurements made in that phase is somewhat questionable. For instance, one of the factors which affect the conductivity in the third phase is the dispersion which took place in the first phase; this dispersion may not occur in the field. Therefore, it seems better to eliminate every possible source which affects the conductivity in the first and second phase with a view to achieving a value which remains nearly constant for some time. Moreover the determinations should be done in circumstances which match those in the field as closely as possible.

For these reasons, soils were saturated with water before measurements were taken and thus further swelling during the measurements did not take place. In this way also the natural degree of swelling was approached as the sites of the investigated layers were close to the ground water table and thus the soils were also at maximum swelling in the field. Moreover, the samples were percolated with a dilute salt solution to prevent dispersion. This too is in agreement with the conditions in the field; the soil solution also contains salts and dispersion is never met in the field. Further the air was evacuated from the soil before the tests commenced and air-free water was used with the intention to prevent evolution of air during the measurement. Also in this respect the conditions were similar to those in the field, as very little air is found in the deeper soil layers. Finally, to prevent microbiological processes which could lead to the blockage of pores a few drops of toluene were added to each liter of the percolating water.

Further problems met with during the tests

In spite of all these precautions, conductivity values obtained in preliminary trials were far from constant with time. Some of the figures obtained are shown in table 6.

TABLE 6. Hydraulic conductivity of disturbed samples, determined by the laboratory permeameter method.

U figure of sand and % clay	Conductivity (m/d) after hours of starting the experiment			
	0	3	6	22
43–0	17.3	13.9	9.5	2.7
170–0	1.54	1.40	1.18	1.18

It can be seen from this table that the decrease of conductivity is stronger when the conductivity is higher. The extent of the decrease varied rather in different cases; in the test shown the drop of conductivity was sharp, but in other cases it was frequently not as marked.

Observation suggested that the pores of the nylon filter, on which the soil column stood, had become blocked by sand particles during the measurement. Other filters were therefore tested and glass wool was found to give more satisfactory results. Table 7 shows a comparison of conductivity values obtained with two types of filters; the first filter consisting of two pieces of nylon cloth, one between the two perspex plates and the other over the upper plate; the second filter consisting of one piece of nylon cloth between the perspex plates and glass wool over the upper plate.

TABLE 7. Hydraulic conductivity of disturbed samples, determined by the laboratory permeameter method using different filters.

U figure of sand and % clay		Conductivity (m/d) after hours of starting the experiment		
	Used filter	0	2	22
43–0	2 nylon clothes	16.0	13.6	1.84
43–0	1 nylon cloth with glass wool	16.3	16.1	12.3

It is obvious from the figures shown above that the glass wool had prevented the decrease of conductivity to a large extent though not completely. It seemed likely from these data that the cause of the drop might be found in the lower part of the permeameter. After testing all kinds of possibilities, it was decided to attach piezometers 1.5 cm from the base of permeameters. This was done by connecting a perspex tube through the side of the permeameter. Glass wool was inserted in the opening of the tube to prevent sand from entering it.

The conductivity was now measured for the part of the soil lying between the level of this opening and the top of the soil column; the hydraulic head in this part of the soil column is the difference in water level between the piezometer and the permeameter itself. Owing to the small adhesion between the perspex and the water and the wide bore of the piezometer, the capillary rise in the piezometer could be neglected.

With this modification some tests were made, the results of which are shown in table 8.

TABLE 8. Hydraulic conductivity of disturbed samples determined by the laboratory permeameter method in the whole soil column and in the upper 9 cm.

U figure of sand and % clay	Conductivity (m/d) after hours starting the experiments			
	0	3	7	9
		In the whole soil column		
43–0	16.8	16.8	12.0	10.8
43–10	6.4	5.9	5.2	4.6
100–0	3.2	3.1	2.8	2.8
170–0	1.53	1.51	1.46	1.46
170–10	0.86	0.82	0.80	0.80
		In the upper 9 cm of the soil column		
43–0	17.7	17.7	16.3	16.3
43–10	6.8	6.5	6.5	6.0
100–0	3.2	3.1	3.1	2.9
170–0	1.51	1.56	1.49	1.49
170–10	0.88	0.82	0.80	0.80

The results cited in this table indicate in the first place that the decrease in conductivity, calculated for the whole soil column, is greater when the conductivity is higher; the decrease is not very sharp with the finest sample, but very pronounced with the coarsest one. If these measurements, however, apply to the upper 9 cm, then the conductivity, even with the coarsest sample, can be considered to be fairly constant. Moreover the results prove, that the decrease in conductivity is due indeed to some alteration in the lower part of the permeameter.

The most important result of this series of measurements – and many others showed the same – is that as a result of the precautions taken (low hydraulic gradient, upward flow of water, use of a dilute salt solution, desinfection of the streaming water, measurement of the conductivity only in the upper 9 cm of the soil column and the use of de-aired water*) it is possible to get constant values over a period of at least 15 hours, a period long enough not to worry about the difficulties in the conductivity-time curve, met by other investigators.

Hence measurements of conductivity quoted in the coming chapters were obtained and calculated in the manner described. The measurements took place at about 3 hours after the start of the experiment; this time was necessary for the water in the piezometers to reach equilibrium when dealing with clayey samples. The experiment lasted until sufficient percolate had been obtained (1–20 cc, according to the permeability of the sample).

With these precautions, values of conductivity were not only constant but also very reproducible as seen from table 9.

* It is very doubtful whether the de-airing yielded indeed air-free water (see page 34).

TABLE 9. Reproducibility of the hydraulic conductivity of disturbed samples, determined by the laboratory permeameter method.

U figure of sand and % clay	Conductivity (m/d) of replicates			
	1	2	3	4
43–0	17.7	17.7	17.7	16.8
43–10	6.8	6.3	6.2	6.4
100–0	3.4	3.2	2.9	3.1
170–0	1.5	1.51	1.54	1.5
170–10	0.79	0.77	0.84	0.84

THE CAUSE OF THE DECREASE IN HYDRAULIC CONDUCTIVITY

Although the direct purpose of this research was not the study of methods of measuring conductivity, nevertheless the very intriguing problem of the decrease of conductivity for the lower part of the soil column led to some other investigations. Further observations suggested that the original assumption that the pores of the nylon filter were blocked with sand particles was unjustified and it was supposed that, in spite of all the precautions taken, the water used was not totally free from air*. This could probably lead to evolution of air in the lower part of the soil column, thus blocking the pores and hindering the passage of water. This in turn could lead to a decrease in conductivity.

To test this assumption, the conductivity of a very permeable sample (U 43) was determined in three ways. In the first test, the measurement was made in the normal way. In the second test the water was allowed to pass through a soil column so that any remaining air could evolve in this column. Thereafter this water was led into the permeameter proper by means of a closed circut. In a third test, the same de-aired water was used but this time after air bubbles had been allowed to pass through, resaturating the water with air. Also in this test the circuit of the water was closed to prevent the results being influenced by any outside factors. The following results were obtained.

TABEL 10. Hydraulic conductivity of disturbed samples determined by the laboratory permeameter method, in the whole soil column using water with three different air contents.

Type of water	Conductivity (m/d) after hours of starting the experiment			
	1	2	4	7
Normal water (de-aired in the usual way)	17.3	—	13.9	9.5
Water further de-aired by passage through soil column	15.5	15.2	14.2	14.8
Above with air re-introduced	10.9**	9.8	7.7	5.5

* Analyses, carried out after the completion of this research, indicted that the water, de-aired in the way described above, contained indeed an appreciable quantity of air.

** Obviously in this test the decrease of conductivity had begun already after one hour.

It was clearly obvious from these results that the decrease of conductivity can be mainly attributed to the influence of air in blocking the pores of the lower part of the soil column. It is also obvious why the decrease was more conspicuous in the more permeable sands as here the quantity of water – and for that reason also that of air – passed during the measurement was greater; hence more air could evolve in the lower part of the permeameter. At the same time it was now possible to explain why the decrease of conductivity for samples having the same permeability was not always the same; the air content of the water may have differed from case to case. Similarly, the superiority of glass wool as a filter was probably based on the fact that in the glass wool considerable quantities of air can separate from the water before it hinders the water passage.

In another experiment, piezometers were installed at different levels of the permeameters. This test suggested that the decrease of conductivity, which begins from the lower part of the permeameter, gradually penetrates further up the column. The fact that the conductivity of the upper 9 cm of the coarsest sample (U 43) was not totally constant, can probably be explained in this way.

Sillanpäa (1956) found that the decrease of conductivity can be removed at least temporarily by reversing the direction of water flow. He attributed the decrease of conductivity to dispersion followed by transport of soil particles during the time of measurement. These transported soil particles might accumulate at narrow points and block them. By reversing the direction of the water flow these particles are punctured and thus could be freed; as a result conductivity increases. However, this increase is only temporary because the clay particles again accumulate at other narrow points and again block them.

Observations made in this study agreed closely with those of Sillanpäa. When the conductivity had decreased with the course of time, it could be increased directly by the reversion of the direction of water flow whereby half of the conductivity decrease was eliminated. However, this increase soon was followed by a rapid drop in conductivity and then further by a gradual decrease.

But Sillanpäa's explanation can be applied also when air bubbles are supposed to be the reason of the decrease in conductivity. The air bubbles evolving from the water, might be pressed into narrower parts of the pore system by the influence of both the hydraulic head and the buoyancy i.e. the air acts as a valve blocking the flow. By reversing the direction of flow, the action of the hydraulic head comes to work against that of the buoyancy and the air bubbles immediately lose in any case part of their valve function. In the long run, however, they will eventually take up new positions in which once again the pores are blocked.

Hydraulic conductivity determinations in undisturbed cores by the field permeameter method

As was said before, the variability of conductivity values for natural soils is much greater than that of the homogeneized. This variability is even so great that it is impossible, with a limited number of cores investigated, to get more than an approximate value of the mean conductivity of the soil. Therefore in this case it is meaningless to endeavour to search for a very accurate method, as a rather rough method, provided it does not give fundamental faults, can offer even as useful data. For this reason the undisturbed cores were investigated in a transportable apparatus which could be used in the field and hence was not as accurate as the laboratory apparatus. More important than the method of investigation is the selection of the sample spots and the way in which the cores were taken. Major attention was paid to these points.

In the first place it was important to get samples which were free from holes (root channels and animal holes); these pores have only little importance for the conductivity of the natural soil but they influence the determination in the permeameter rather strongly. Samples were therefore obtained from regions just above the ground water table where these holes are seldom met with. This had the advantage too that the samples originated from the deeper layers, which are the most important for the flow of water. In this respect it is further important that the soil in these deeper layers tends to be at maximum swelling and of a low air content.

The sites from which the samples had to be taken were firstly roughly surveyed and then, provided it appeared that there was a layer as homogeneous as could be possibly found, samples were taken from it. The pressing of the cylinders in the profile was done without twisting or turning so that the cylinders were totally filled with the soil in its natural state. All the investigated samples were rather wet and contained some clay, thus allowing the cylinders to be pressed in easily and without great effort. As far as could be felt, this process caused no compaction of the samples and effected a tight connection between the cores and the walls of the permeameters.

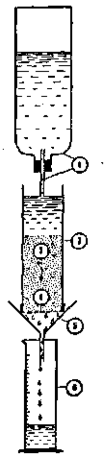

FIG. 5. Apparatus used for the determination of the hydraulic conductivity of undisturbed cores in the field.

1. mariotte system
2. permeameter
3. soil
4. filter
5. funnel
6. collecting bottle

The cylinders in this study had a length of 20 cm and a diameter of 7 cm and were pressed in the soil with the help of a piece of wood. When they were dug out, the excess of soil was cut away gradually and carefully so that the end was not smeared. The cores were inspected carefully; abnormal cores were not analysed but replaced by other ones. For the determination of the conductivity first the bottom of the cylinder was covered with a piece of filter paper and then a cap, which consisted of a gauze sieve, was fitted over it. After this the cylinders were suspended on a rack and supported from beneath by funnels leading to bottles in which the percolating water was caught. The measurement was made with tap water. As shown in fig. 5, the percolating water was delivered by a Mariotte system to keep the water at a constant level (about 5 cm above the surface of the column). Thus hydraulic gradients were about 1,5 which was a much higher value than that used in the laboratory method.

The measurement took place as soon as the process of percolation seemed to have attained equilibrium. The experiment lasted till sufficient percolate had been obtained (about 100 cc); the time needed ranging from 15 minutes to 2 hours. This procedure and apparatus was for the most part adapted from that used by KOPECKY (1914) and will be referred to as the field permeameter method.

Ten cores were taken from every spot investigated. If the conductivity of one or more cylinders showed serious deviations from the average, the core was thoroughly examined. In most cases it was possible to ascertain the cause e.g. poor connection between the soil column and the wall of the permeameter, or holes extending in the cylinder from top to bottom. In such cases the results were discarded. In a later stage 5 cylinders from the 10 were pushed vertically into the soil and the other 5 horizontally As it appeared that the vertical conductivity differed from the horizontal, while the horizontal is the most important, the results of the vertical cylinders were discarded. Hence part of the data used in chapter IV, are the mean of 5 cores.

As already mentioned, the conductivity of the different columns (taken from one sample spot) varied to some extent. Table 11 gives some representative data about the reproducibility of this method.

TABLE 11. Reproducibility of the hydraulic conductivity of undisturbed cores, determined by the field permeameter method.

U figure of sand and % clay	Conductivity of replicates (m/d)									
	1	2	3	4	5	6	7	8	9	10
56–0.5	7.1	6.6	6.2	7.4	6.6	7.2	6.4	7.4	6.4	—
121–1	1.07	1.13	1.40	1.30	1.45	1.15	1.01	0.92	1.19	—
207–76	0.12	0.11	0.12	0.12	0.12	0.11	0.11	0.13	0.08	—
340–5.7	0.12	0.13	0.14	0.15	0.15	0.13	0.12	0.16	0.15	0.14

RELIABILITY OF THE RESULTS OBTAINED BY THE FIELD PERMEAMETER METHOD

Many precautions were taken in investigating the disturbed samples at the laboratory to get results which were as reliable as possible. Such precautions were not taken in the field measurements and the question can arise whether or not this could have led to fundamental errors. To test this the laboratory apparatus was modified to fit for the determination of the conductivity in undisturbed cores. This was done by a method, applied by WIT (1961). The size of these cores was smaller than those of the field apparatus, about 5 cm long and 5 cm wide.

Thus it was possible to investigate these samples in the same manner as the disturbed ones: before the determination of the conductivity the cores were evacuated and saturated with water and the measurements were made with a low hydraulic head and with a dilute salt solution. Consequently primary present air did not influence the results and microerosion, dispersion and transport of clay particles could not take place. Thus the results of these experiments, as to these possible errors, can be fairly considered as correct. One of the greatest difficulties accompanying the determinations of the conductivity in disturbed samples in laboratory permeameters was the evolution of air from water at the lowest part of the permeameters which impeded the passage of water. These difficulties were avoided in the disturbed samples by restricting the measurements to the upper part of the permeameter. For the undisturbed cores this was not possible so that an experiment to test whether also in this case there was a change of conductivity with time seemed necessary. The results of this test are given in table 12.

TABLE 12. Hydraulic conductivity of undisturbed cores, determined by the laboratory permeameter method.

U figure of sand and % clay	Conductivity (m/d) after hours of starting the experiment			
	3	6	9	18
72–1.8	5.5	5.6	4.6	1.3
249–3.5	0.52	0.55	0.55	0.55
225–3.3	0.26			0.26

From these results it appears that a decrease of conductivity also found place with the undisturbed cores. Similar to the case of the disturbed samples, this decrease was more rapid and conspicuous as the samples were more permeable. Because all other known factors contributing to the fluctuation of conductivity were avoided, it is probable that evolution of air is here also the reason of this decrease. This means that the first reading of conductivity is the most fitting. Moreover it is clear from table 12, that the conductivity remains constant – and thus correct – for a period long enough for succesful determinations.

It can be concluded that in determining the conductivity of undisturbed cores obtained by the way explained here above (evacuation of air and saturation with water beforehand, percolation with a low hydraulic head and by a dilute salt solution) all possible errors are avoided. The question now arises how will be the results of the field method in comparison with that above. To investigate this, 5 layers were investigated in 5 replicates and the results are shown in table 13.

TABLE 13. Hydraulic conductivity of undisturbed cores, determined by the laboratory and field permeameter method.

U figure of sand and % clay	Conductivity (m/d)	
	Laboratory permeameter method	Field permeameter method
72–1.8	4.1	4.4
80–1.8	2.5	2.5
249–3.5	0.52	0.49
225–3.3	0.26	0.20
170–6.0	0.17	0.18

From this table it appears that the field permeameter method gave about the same results as the more accurate laboratory permeameter method. This is probably thanks to the fact that the samples were obtained and the measurements were made in such a way that certain drawbacks were avoided beforehand. In the first place the clay content of the samples was low and they were taken close to the ground water table; so the likelihood of much swelling was very slight. In the second place, in the deeper layers from which these samples were chosen, air content is at a minimum so that its influence on the measurement could be neglected. In the third place, the conductivity was determined as soon as possible after starting the experiment and the duration of the measurement was only short, so that air evolution is not expected to influence ther esult. The rather high hydraulic gradient used, obviously did not cause transport of clay particles and consequently blockage of pores did not take place. Finally the shifting from a diluted salt solution (de-aired) to normal tap water has had no influence on the percolation, probably due to the short duration of the experiment.

It can be thus concluded that the field permeameter method is probably not susceptible to systematic errors in this type of soils (sandy soils at maximum swelling, low air content) and that the results obtained are reliable.

HYDRAULIC CONDUCTIVITY MEASUREMENTS BY THE AUGER HOLE METHOD

The main disadvantage of this method is that it is even more difficult to get representative and homogeneous spots than when the field permeameter method is used. Also in this case determinations were only carried out after surveying and accurately inspecting the soil profile in order to obtain the required type of soil in a sufficiently homogeneous condition. However the standards of homogeneity could not as strictly be imposed as with the field permeameter method.

The upper dry layer of the profile was bored by a screw auger (diameter 7 cm). However, this method is not suitable for saturated sandy layers and as soon as such layers were reached, a copper tube (7 cm wide) was lowered in the hole to this depth and was pushed further in, the hole being deepened with the help of a bailer. With such precautions disturbance of the profile and moving of sand in the hole was prevented. Moreover in sandy soils, puddling of the walls of the hole caused by the friction of the tube is not likely to occur. Because the copper tube had to remain in place during the measurement it was made with perforations and also wrapped in a layer of jute tissue. The resistance of this arrangement proved to be negligible.

Usually measurements took place after at least one day had elapsed during which time the ground water table was allowed to attain equilibrium. This period of time was sufficient for the type of soil investigated in this study. The water in the hole was rapidly pumped out with a bailer and the velocity of the water ascent was measured as soon as possible. This was carried out by placing a float provided with a light weight steel tape on the water surface in the hole. Thus, with the use of a standard, the time was recorded to reach specific stages in the ascent of water. For most soils this distance was 1–2 cm but for very impermeable soils 0.5 cm and for very permeable ones 5 cm.

The time elapsing between measurements varied from 2 till 100 seconds according to the soil conductivity; measurements were continued until a quarter of the water which had been pumped out had been replaced. The first time interval recorded was always ignored. The results obtained were calculated from the formula mentioned in chapter I, the conditions imposed by the formula being strictly applied.

The thickness of the layers, in which the conductivity was measured, was usually about 50 cm. However, it was not always possible to find homogeneous layers of this thickness. Thus sometimes the measurements had to be carried out in thinner layers, but never thinner than about 30 cm. For every representative spot, the conductivity was measured in 2 holes which in the rather homogeneous soils tested proved to be a sufficient number. Table 14 gives some representative data on the reproducibility of this method.

TABLE 14. Reproducibility of the conductivity in natural soils, determined with the auger hole method.

U figure of sand and % clay	Conductivity of replicates (m/d)	
	1	2
68–3	4.2	4.8
71–2	2.3	3.1
77–1	3.4	3.4
89–2	1.5	1.4
290–4	0.24	0.20
300–5	0.26	0.24

As to the reliability of the auger hole method for the determination of the hydraulic conductivity, it can be assumed that Ernst's formula is correct within the limits given (see page 14). Also with model experiments it was found that the conductivities determined were not affected by the diameter and the depth of the hole or by the quantity of water pumped out (HOOGHOUDT, 1936).

Both the auger hole and the field permeameter method are based on the flow of water in undisturbed soils. Thus it can be assumed that certain methodical difficulties, connected with the laboratory permeameter method do not affect the auger hole method any more then they proved to affect the field permeameter method (e.g. changes in the air content during the measurement and dispersion of the clay particles).

Circumstances under which the measurements are made in the field cannot be varied as much as in the laboratory and thus this method cannot be as easily subjected to methodical investigation. Apart from variations in diameter and depth of the hole and of the quantity of water pumped out – which factors have been tested already by HOOGHOUDT – the only other possible variation is a repetition of the measurement in the same hole. Especially puddling of the walls of the hole can be detected in this way as a repeated waterflow from the soil to the hole would reopen more or less the smeared surface of the hole. This repetition of the measurements was tried in several profiles and the results are shown in the table below.

TABLE 15. Repeated measurements of the hydraulic conductivity in natural soils, determined by the auger hole method

U figure of sand and % clay	Conductivity (m/d) of repetitions	
	1st time	2nd time
68–3	4.1	4.2
71–2	2.4	2.1
77–1	3.7	3.1
89–2	1.4	1.5
290–4	0.25	0.22
300–5	0.20	0.28

From these figures it can be seen that the conductivity of the successive measurements was about constant. This may thus be taken as an indication that puddling of the walls of the holes in these soils did not take place.

It is also possible to obtain some idea of the reliability of the method by comparing the auger hole conductivity values with those obtained by other methods. Within a limited range this has been done by KIRKHAM AND DE ZEEUW (1952). In this study it has been possible to extend the range of comparison to other types of soils and it is hoped that the results of these large scale comparisons may contribute to a better understanding and assessement of the auger hole method.

X HYDRAULIC CONDUCTIVITY MEASUREMENTS BY THE DRAIN DISCHARGE METHOD

In principle the best evaluation of conductivity, as already mentioned in chapter I, is obtained from the measurement of the drain discharge. The conductivity can be calculated from this drain discharge and the connected ground water table by the formula given in page 16. In practice, however, it is difficult to find the cases in which this principle could be applied; calculations are difficult or impossible if the soil is not fairly homogeneous and when it is not known – which is often the case – wether an impermeable layer exists or not.

For this study quite a number of measurements of drain discharges and ground water table levels, carried out in the Zuiderzee polders, were available, but the above mentioned conditions were only satisfied to a certain degree and in a few instances. Indeed, it appeared that the results of no more than 13 of the 24 plots available were suitable for this investigation.

The measurements of ground water table and discharge of drains were carried out during the wet season (about 15 Nov. till 15 Febr.) in parcels of a length of 800 m and a width of 300 m, bordered on both sides by larger ditches 1 m deep and crossed by smaller ditches (field ditches). These field ditches were originally about 60 cm deep, but had tended to fill up rather so that the effective depth in fact was somewhat less. The distances between these field ditches ranged from 8 till 60 m depending on the soil conductivity. Each field ditch was divided down the middle by a dam and for this reason only half of the length of each plot (150 m) and half the length of the field ditches entered into a given measurement, but for convenience's sake the terms 'the plot' and 'the ditch' are retained for the following discussions.

On every plot it was usual to investigate a serie of 3 field ditches, piezometers being placed midway between the field ditches on a distance of 110 m from the main ditch. To record the waterlevel in the field ditches, gauges were placed in them. The piezometers were constructed from 2½ cm wide perforated iron tubes and wrapped in a layer of jute tissue; such piezometers react very rapidly to the fluctuations of the ground water table in this type of soil. Measurements of ground water table and water level in the ditches were carried out once a day and related to the average plot level. As the corresponding ground water tables and water levels in the field ditches varied only slightly, values of both were averaged for every day over the whole plot.

The field ditches discharged into a series of tile drains, with a length of 10 m, running under the head of the plot, at the ends of which were installed gres-tubes of 1 m length. The discharge of the field ditches was measured with the help of a volumetric can and a stopwatch once a day and was converted to m/24 hours. The drain-tiles were not quite watertight. Thus part of the water leaked through the subsoil of the head to the main ditch; even from the field ditch itself some water may had seeped away. Consequently, as the whole discharge was not measured, a correction for the leakage had to be made (see page 43).

The average discharge over the whole wet season usually varied only slightly from field ditch to field ditch and for that reason the daily discharges of the different field ditches were averaged.

There were, however, sometimes considerable discharge differences between some of the corresponding field ditches on one day.

The average ground water table midway between the field ditches and the average water level of the ditches were plotted every day against the average discharge and fig. 6 gives a representative example in which it can be easily seen that a relationship exists between the ground water table, the water level and the discharge. The points on the graph showing the relationship between discharge and water level in the field ditches lie very close to the line but on the graph relating ground water table and discharge some points are rather scattered.

Such deviations tended to occur if observations had been made shortly after rain had fallen and a number of reasons can be advanced to explain this. In general these reasons all amount to the same fact, namely that immediately after rain has fallen a number of abnormalities occur and the mutual relationship between ground water table and discharge is disturbed. For all practical purposes such data can be ignored and a line can be drawn through the rest of the points.

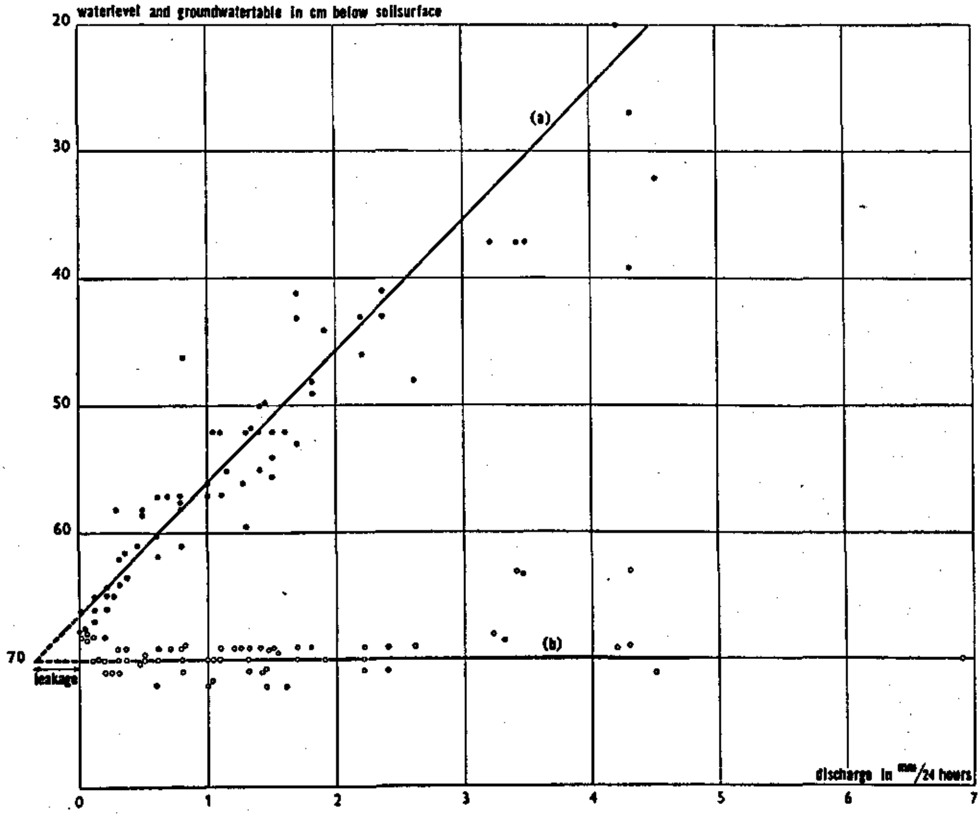

FIG. 6. Relationship between the discharge and the ground water table midway the field-ditches (a) and the waterl evel in the field-ditches (b).

Curves obtained in this manner all showed the same satisfactory degree of relationship between ground water table and discharge that is shown by the formula mentioned on page 16. This is most obvious for these cases where there was an upper homogeneous permeable layer of the soil of a considerable thickness. If it is assumed, for the sake of simplification, that there is no water standing in the field ditches, and $K_1 = K_2$ the formula in page 16 can thus be changed to

$$S = \frac{4K}{L^2}(2d + m)m$$

If the thickness of the permeable layer is big enough, m becomes small in comparison with 2 d, and the term 2 d + m is more or less constant and thus the relationship between ground water table (m) and discharge (S) must be linear. That this indeed is the case can be illustrated by the example shown in fig. 6. Deviations from this linear relationship were found – and they were sometimes quite appreciable – only in the case of very high ground water tables and discharges. One of the main reasons for this phenomenon is that after heavy rainfall some of the water which is discharged into the field ditches has simply run off the soil surface. Thus the discharge is greater than corresponds with the ground water table and points lying on the right hand side of the line can be neglected.

The lines which are drawn through the clustered points give an average relationship between the ground water table and the discharge for all the observations and may therefore be regarded as being fairly reliable as such. In some plots the observations were carried out for two successive years during which new piezometers are installed. The line, found in the second year, deviated in all the cases only slightly from that of the first.

The lines for the ground water table and the water level in the field ditches should meet at discharge = 0; there is however a gap between them. This is due to the leakage to the main ditch. This leakage can be found by extrapolating both lines till they meet (see fig. 6). In calculating conductivities, the discharge measured has been increased with the lost part.

Another difficulty met with was that rainfall in a parcel was not totally discharged via the field ditches; part of it was directly drained by the main ditch. In consequence of this extra discharge the ground water table near the main ditch was lower than further on the parcel and the ground water table on which the calculation of the conductivity was based (110 m from the main ditch), was higher than the average ground water table in the parcel; this average ground water table, however, is the one which has to be connected with the discharge. Consequently the conductivity calculated was too low and had to be corrected. For soils with a low conductivity and thin aquifer, this correction is negligible; but even for more permeable and bigger aquifers the correction proved to be at most 15%. Thus, an incorrect estimate of the correction would not lead to a great error in the conductivity calculated.

For the calculation of the conductivity proper an arbitrary point is chosen in the ground water table-discharge curve and then the related discharge, ground water table and water level in the ditches are inserted in the formula.

The reliability of these curves for the calculation of conductivity seems, in particular, to be confirmed by the work of VAN DEEMTER (1950). From detailed studies of the relationship between ground water table and discharge he reached the conclusion that – in cases such as this and within the limits of the assumptions made – HOOGHOUDT's formula expresses the relationship satisfactorily.

One of the assumptions in the derivation of this formula, however, is that an equilibrium state should exist between the inflow and outflow, in other words that the intensity of rainfall should always be constant and that the height of the ground water table midway between the field ditches should therefore attain a constant value. These conditions are nearly never satisfied in nature as the rainfall occurs intermittently and consequently the ground water table in question is rising and falling.

According to the calculations of KRAIJENHOFF VAN DE LEUR (1958), the discharge of a rising ground water table is greater than that occurring in the equilibrium state and similarly smaller in the case of a falling water table. He also states that the relationship between the discharge and the ground water table in an equilibrium state lies in between the relationship found for rising and falling ground water tables. So a certain degree of scatter can be expected and the average curve drawn through the most clustered points very probably represents the equilibrium relationship and is thus the best for the conductivity calculations.

Unfortunately, particularly in the lowest part of these graphs, there was no systematic difference between the data obtained in cases where there was a rising or falling water table. Thus the question of the meaning of this scatter and of its significance in measurements of conductivity remains unanswered. On the other hand it is reassuring to realize that the line drawn is the average relationship between the discharge and the ground water table; conductivity calculated from this line is in any case the deciding factor in drainage itself.

A further difficulty in the conductivity calculations lies in the structure of the profile. In all the investigated cases an not ripened layer of clay or humus-detritus was found in the profile with at least 50 cm thickness, and usually from 100–400 cm. Enough is known about such sediments to assume that they are almost quite impermeable (ZUUR 1958) and that they totally prevent the downward passage of water. These impermeable layers were deposited at the bottom of a lake and are therefore expected to be found in the subsoil of the whole observation area. The top of this impermeable layer – and of the transitional layer, discussed hereafter – was however not always, as might be expected for a lake deposited sediment, quite flat because of compaction which differed with its thickness. To determine the depth of the impermeable layer 2 borings were carried out; this depth varied sometimes as much as 15% from one spot to another. Thus the calculated average thickness of the permeable section was burdened with a rather big error and therefore the calculation based on such averages are also subject to a certain amount of error.

Between the impermeable layer and the usually fairly homogeneous upper layer, in which the conductivity had to be determined, a transitional layer was frequently encountered. The U figure of this layer was at least 150 and the clay content 8%. From the results, discussed in chapter IV, it can be assumed that the conductivity of such layers is at the utmost 0.1 m/d, probably much less.

For the calculation of the conductivity of the upper layer, a variant of the formula discussed in chapter I was used, in which allowances are made for the existence of two different conducting layers over the impermeable layer. With this formula the conductivity of the upper layer was calculated in two ways: firstly assuming the conductivity of the transitional layer to be 0.1 m/d, secondly to be 0 m/d. In all cases the relationship between thickness and conductivity of the upper layer on one hand and thickness and conductivity of the transitional layer on the other was such that both calculations yielded a difference of utmost 10% for the conductivity of the upper layer. Thus an erroneous estimate of the conductivity of the transitional layer – estimated at 0,1 m/d – has only a very limited influence.

In general it can be concluded that although the determination of the conductivity from the ground water table-discharge curve is fundamently the most fitting method, many uncertainties can arise in the interpretation of the results.

III. THE HYDRAULIC CONDUCTIVITY OF PURE SANDS AND THE INFLUENCE OF ADDED CLAY PARTICLES ON IT

THE PURE SANDS INVESTIGATED

It has been repeatedly mentioned that in sandy soils there is a relationship between the hydraulic conductivity and the coarseness of the sand and the clay content. These relationships will be dealt with more fully in this and the following chapter. It is perhaps easiest to consider first the case of pure sands which contain no clay, as here the relationships between the particle size of the sand and the geometry of the pore system is not complicated by the presence of clay aggregates blocking the pores.

As sandy soils without any clay do not exist in nature, 43 sandy samples of different textures were washed with water till the supernatant liquid was clear (i.e. 5 to 20 times). Even then some traces of clay still remained in the samples but the percentage was relatively small (0.4 till 1.8%). The samples were then dried and allowed to pass a 2 mm sieve. Of the 43 samples 35 were of marine origin, 30 being from the Zuiderzee polders and 5 from polders of Groningen. Because marine sediments seldom contain coarse deposits also 8 samples were taken from fluviatile soils in Gelderland. All the samples were then investigated by the laboratory apparatus described in chapter II.

THE RELATIONSHIP BETWEEN GRANULAR COMPOSITION AND CONDUCTIVITY

There is no stronger proof of the need for estimating conductivity from the granular composition than the number of efforts (often very old) which have been previously made to establish this relationship by such workers as SEELHEIM (1880), HAZEN (1895), SLICHTER (1899), KRÜGER (1918), TERZAGHI (1925), KOZENY (1927), ZUNKER (1930), HOOGHOUDT (1934), CARMAN (1939), ROSE (1950) and LOUDON (1953).

A study of all these formulas gives the impression that a great deal of confusion existed regarding the concept of 'permeability'. Thus each of the terms ρ, g and η may or may not be present in the formulas. If not mentioned as such, they are incorporated in the 'constant' of the formula. This certainly led to all kinds of difficulties with respect to the dimension of the calculated conductivity; hence for sake of comparison it is necessary to bring all these formulas to the same basis, which in this study has been taken as the hydraulic conductivity expressed in m/d at 10° C.

A comparison of the formulas on this basis shows that, as a matter of fact, in all of them conductivity is dependent firstly on the size of particles but moreover on a number of other factors. One of them is the porosity expressed as the part of the total soil volume occupied by the pore space. In some (in particular older) formulas (SEELHEIM AND HAZEN) this factor is absent; but when present its influence is indicated by various functions: $\frac{p}{(1-p)^2}$ (KRÜGER revised by ZUNKER), $\frac{p^2}{(1-p)^2}$

(SLICHTER revised by ZUNKER and ZUNKER), $\frac{(p - 0.13)^2}{\sqrt[3]{(1-p)^2}}$ (TERZAGHI) and $\frac{p^3}{(1-p)^2}$ (KOZENY followed by CARMAN AND HOOGHOUDT). LOUDON (1953) indicated the influence of porosity by an exponential term; according to him this function renders the same results as the Kozeny formula and so this type of function is not discussed further.

In order to get information on the influence of porosity on conductivity of marine sands, 4 samples of different textures were investigated at different porosities. The samples were firstly investigated in the normal way (as indicated in chapter II), which renders a very low porosity. In another test these samples were merely placed loosely in the permeameters without dropping them before evacuation of air or after saturation with water. The conductivities obtained in these two different ways are compared in table 16. The letters A and B indicate high and low porosities respectively, while $\frac{p}{(1-p)^2}$ A indicates this factor at high porosity.

TABLE 16. Hydraulic conductivity, determined by the laboratory permeameter method, and porosity factor of a number of pure sands at different porosities.

	U figure of sand			
	43	90	170	205
Hydraulic conductivity A (m/d)	22.1	5.1	2.4	1.78
Hydraulic conductivity B (m/d)	11.8	2.8	1.20	1.17
Hydr. conductivity A: Hydr. conductivity B	1.87	1.82	2.00	1.52
Porosity A	37.7	38.3	44.4	43.5
Porosity B	31.3	33.3	38.8	39.4
$p/(1-p)^2$ A : $p/(1-p)^2$ B	1.47	1.34	1.39	1.26
$p^2/(1-p)^2$ A : $p^2/(1-p)^2$ B	1.77	1.54	1.59	1.39
$(p-0.13)^2/\sqrt[3]{(1-p)^2}$ A : $(p-0.13)^2/\sqrt[3]{(1-p)^2}$ B	1.88	1.63	1.58	1.38
$p^3/(1-p)^2$ A : $p^3/(1-p)^2$ B	1.91	1.76	1.82	1.54

The porosity had an influence on the conductivity as clearly shown from the table and it can be concluded that the formulas in which the porosity factor is absent can be left out of consideration. The results of this investigation suggest that the function $\frac{p^3}{(1-p)^2}$ is most satisfactory, thus confirming the observations of HOOGHOUDT, CARMAN AND LOUDON and it has therefore been used in all subsequent calculations in this chapter.

The different formulas also contain a factor in which the complete granular composition is expressed by one parameter. This parameter is either some representative particle diameter or it is a measure for the total surface of the particles. The representative particle diameter is the average particle diameter (e.g. SEELHEIM) or the 'active particle diameter' (ZUNKER). The manner of obtaining these diameters is frequently not given (e.g. SEELHEIM, SLICHTER).

The particle surface may be given as specific surface (U figure; see page 22) (ZUNKER, 1930; HOOGHOUDT, 1934), as absolute particle surface per unit volume soil (KRÜGER), or as absolute particle surface per unit volume particle or unit weight soil (CARMAN). These surface parameters are easily interconvertible, though the pore volume must be included when these formulas are converted to or derived from the type of factor used by KRÜGER.

In all these formulas it is assumed, either in the derivation of the formula, or in the application, that the particles have a spherical shape (though sometimes a correction for the lack of sphericity is used). Thus in comparing the different formulas the particles can be assumed to be spherical. With spherical grains the (representative) particle diameter is proportional to the reciprocal value of the total particle surface per unit soil weight (ZUNKER, 1930). Thus the parameters of the particle diameters can be converted to surface measures. If the U figure is chosen as parameter for the surface it appears that in all the formulas the conductivity is inversely proportional to $\frac{1}{U^2}$ and so this factor is the one which will be employed.

Besides the factors expressing porosity and particle size all the formulas contain a term (μ) which indicates among other things the numerical relationship between conductivity on the one hand and specific surface and pore volume on the other. In some formulas, a further factor is employed to indicate the 'tortuosity' of the water passage (e.g. KOZENY) and a factor for the combined influences of the particle shape, the roughness of the particles and/or the sorting of the sand. For the time being it can be accepted that for one type of sand (in this case marine sands) these factors are about constant and thus can be included in the term μ. Thus it appears that the relationship between the granular composition and the conductivity can be expressed in the formula

$$K = \mu \frac{p^3}{(1 - p)^2} \cdot \frac{1}{U^2}$$

The problem which then arises is that of determining μ; this has e.g. been accomplished by HOOGHOUDT in Dutch soils using subfractions obtained as byproducts of the granulometric analysis. The results which he obtained from several different subfractions (16–50, 50–75, 75–105 μ etc.) indicated that the value of μ did not differ much from fraction to fraction and thus the average obtained value is commonly used in the Netherlands.

In this investigation tests were made on the pure sands, mentioned above. They had not been fractioned and thus they gave a more representative picture of the kind of thing which might occur in practice. The results obtained are shown graphically in figure 7 in which $\frac{1}{U^2}$ and $\frac{K(1-p)^2}{p^3}$ of the 43 samples are plotted against each other. It appears from this graph that the relationship between particle size (given as $\frac{1}{U^2}$) and conductivity (including the porosity) (given by the factor $\frac{K(1-p)^2}{p^3}$) for the Dutch marine soils is very close. This relationship applies also to the investigated soils not originating from marine deposits. As can be seen from fig. 7 a fairly linear proportion exists between $\frac{1}{U^2}$ and $\frac{K(1-p)^2}{p^3}$ so that the relationship between specific surface and conductivity seems to be correctly given by the formula.

It can be concluded from fig. 7 that the average value of the coefficient μ is 26×10^4. HOOGHOUDT found a value of 25×10^4 and it is highly surprising – and stands for the accuracy of at least part of the assumption given in the formula – that the μ-value is the same for pure fractions and for sands of mixed composition. The value of the coefficient is in the same magnitude as that of KOZENY/CARMAN calculated on theoretical grounds (CARMAN, 1939). However, that this is more or less accidental and certainly not a proof for the intrinsic correctness of the formula can be concluded from the results, discussed at the end of this chapter.

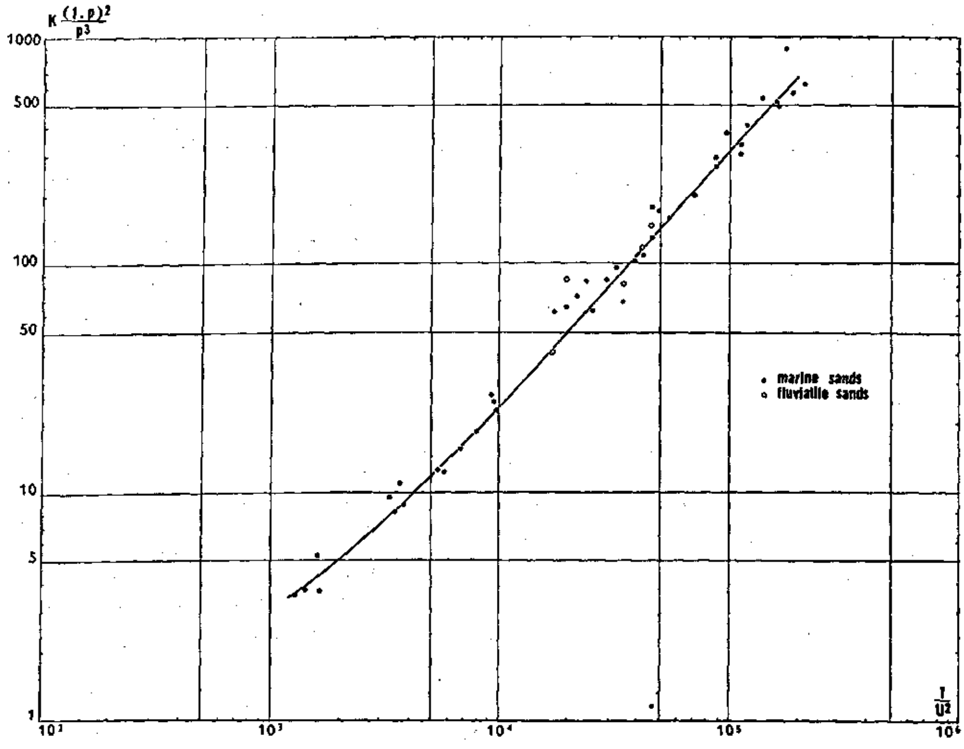

FIG. 7. Relationship between $\frac{K(1-p)^2}{p^3}$ and $\frac{1}{U^2}$ for clay-free sands, K determined by the laboratory permeameter method.

It is difficult to make a comparison between the μ-value of this and that of other formulas because those other formulas express the influence of porosity by another factor. At a fixed porosity a comparison is however possible. Taking the porosity at 0.40 (which is about normal for marine sands in the field) the values of the proportionality factor between K and $\frac{1}{U^2}$, or in other words, for the product KU^2, are as shown in table 17.

TABLE 17. Values of the product KU^2 at a porosity of 0.4 according to several investigators.

Investigator		(K in m/d at 10°c) $KU^2 \times 10^{-3}$
Seelheim	determined	31
Slichter	determined	33
Krüger	determined	36
Terzaghi	determined	40–71
Schönwälder	determined	40
Zunker	determined	32–44
Hooghoudt	determined	44
Fahmy	determined	47
Kozeny/Carman	calculated	65

Although the values given in this table have about the same magnitude, the differences between them are such that the special investigation, carried out for estimating the μ-values of the marine Dutch soils seems to be justified.

As a result of this investigation, it can be stated that for homogeneous Dutch marine sands, free from clay and air, the relationship between particle size and conductivity can be satisfactorily expressed by the formula:

$$K = \frac{\mu\, p^3}{(1 - p)^2} \frac{1}{U^2} \quad \text{where}$$

K = hydraulic conductivity in m/d,
μ = a term with the dimension of $L^{-1}\, t^{-1}$ and which has a numerical value of 26×10^4,
p = porosity, expressed as part of total volume of soil and
U = the ratio between the total surface of all particles and the surface of an equal quantity by weight of particles of the same material with a diameter of 1 cm, with the assumption of the sphericity of the particles.

HYDRAULIC CONDUCTIVITY OF ARTIFICIAL MIXTURES OF SAND AND CLAY

It has already been mentioned in the introduction that the influence of the clay on the conductivity must depend on the way the clay particles occur in the sand. Since in artificial mixtures their distribution differs considerably from that in the field, it is not to be expected that the results obtained from studying these mixtures will be of direct importance in practice. This research has in the first place a methodical value: How do the clay particles tend to behave in the sand and what is the influence of the different manners by which the clay particles are distributed in the sand on the conductivity.

In behalf of these investigations five sandy samples with different textures were collected from sites in the Zuiderzeepolders. The samples were washed and decanted with water a number of times (from 10 to 30 times, according to the fineness of sand and the clay content) until the supernatant liquid was fairly free from clay. The samples were then oven-dried and allowed to pass a 2 mm sieve.

The clay sample which was used in these experiments was an illite clay from Groningen and contained about 46% clay; the calcium carbonate content was about 10% and the exchangeable cations consisted mainly of calcium. This clay was dried, ground and then separated into two fractions of different aggregate size: one between 0.5 and 1 mm, the other between 0.0 and 0.5 mm. Though the size of the aggregates differed, the granular composition was of course the same in both fractions. For the investigations these clay aggregates were mixed in different quantities with the sand. In the tables discussed hereafter, an addition of '10% clay' means 10% of clay aggregates; the actual addition was only about half of it.

The appropriate quantities of sand and clay were first thoroughly mixed on a sheet of paper and then packed in the permeameters by the method described in page 26. If the sample in the permeameter did not appear to be homogeneous (this being easily observed through the transparant walls of the permeameters) the process was repeated until a satisfactory homogeneous condition was attained.

In table 18 the resulting conductivities are given where the coarse fraction of the illite-clay (0.5–1 mm) was used.

TABLE 18. Hydraulic conductivity (m/d) of artificial mixtures of sand and illite clay (0.5–1 mm), determined by the laboratory permeameter method.

U figure of sand	Percentage clay aggregates added				
	0	3	6	9	12
43	17.7	17.7	17.1	16.5	15.3
90	3.5	3.4	3.1	3.0	2.8
120	2.7	2.4	2.4	2.3	2.1
172	1.54	1.56	1.43	1.26	1.16
205	1.21	1.21	1.13	1.05	0.96

It can be seen from this table that the coarse fraction of the clay particles had little influence on conductivity. It is true that the conductivity of the samples with the highest clay content is somewhat lower than that of the pure sands, but the differences are obviously small in comparison with the influence of the finer fraction on conductivity which is shown later in table 19. The fact that there is after all a small decrease is probably due to a slight disintegration of the coarse fraction when mixed with the sand.

Thus when clay particles exist in the sand as coarse aggregates it appears that they have little influence on conductivity. The clay aggregates are too big to fit into the primary pores between the sand particles and to bloc kthem. Consequently, in size and effect they do not differ greatly from sand particles and they contribute in the same way to the building up of the porous skeleton as the sand grains. As a result of this, they have little influence on conductivity.

Further it appears from these results that the clay aggregates retain their granular structure in moist soils. Had this not been the case they would have decreased the conductivity to a greater extent (see the results with the finer clay fractions and with the montmorillonite). Such coarse clay aggregates are thus neither disintegrated in wet soils nor eroded by the streaming water. This applies probably to field conditions as well.

The results of experiments carried out with the finer fraction are given in table 19.

TABLE 19. Hydraulic conductivity (m/d) of artificial mixtures of sand and illite clay (0.0–0.5 mm), determined by the laboratory permeameter method.

U figure of sand	Percentage clay aggregates added				
	0	3	6	9	12
43	17.7	10.24	4.93	2.45	1.33
90	3.5	2.31	1.39	0.90	0.55
120	2.73	1.98	1.23	0.84	0.52
172	1.54	1.19	1.00	0.73	0.46
205	1.21	1.02	0.77	0.56	0.39

It is evident from this table, that the influence of the finer fractions on conductivity is much greater. The conductivity decreased considerably with increase in clay content; with the coarse sand the addition of 3% clay aggregates caused the conductivity to drop to about two thirds of the original value and the addition of 12% aggregates reduced the value to about one tenth of the original.

Also from these results it is evident, that the aggregates contribute to the building up of the porous skeleton. The porosity of the samples containing clay (especially those with the highest clay percentage) was greater than that of the pure sands. This can only happen when at least part of the clay aggregates – which are porous in contrast to the sand particles – contribute to the building up of the skeleton. At the same time it appears from the decrease of conductivity that a considerable part of the finer clay aggregates occupies the primary pores of the sand skeleton and blocks them. Table 20 shows the porosities of the researched samples.

TABLE 20. Porosity (expressed as part of total volume) in artificial mixtures of sand and illite clay (0.0–0.5 mm).

U figure of sand	Percentage clay aggregates added				
	0	3	6	9	12
43	0.33	0.34	0.34	0.34	0.34
90	0.33	0.34	0.35	0.35	0.36
120	0.38	0.38	0.39	0.40	0.41
172	0.40	0.41	0.42	0.43	0.43
205	0.40	0.40	0.41	0.41	0.42

With the same additions of clay aggregates, the decrease of conductivity is greater in coarse sands than in fine ones. This is mainly due to the fact that the primary pores in the coarse sand are bigger and thus not only the smaller, but also the bigger clay aggregates can find their way into these primary pores. This difference between the coarse and the fine sand is borne out by the fact that the increase of the porosity by the addition of clay aggregates is greater in the finer sands than in the coarsest ones. The second reason for the great influence of the clay aggregates on the coarse sand is that the number of primary pores in the coarse sand is smaller and therefore, comparatively, the quantity of blocked pores is greater.

Further, it is apparent from table 19 that the influence of clay aggregates on the conductivity with the finer sand is approximately proportional to the quantity of the clay added while, with the coarse sand, the influence of a small quantity is comparatively speaking much greater than that of a big one. This phenomenon will be discussed in more detail later on in this chapter.

In these experiments the clay exists between the sand particles as granular aggregates although sometimes those may be very fine ones. In nature, the clay aggregates are deposited between the sand particles in very wet condition and therefore their shape becomes highly adapted to that of the primary pores.

In an attempt to reproduce these conditions, some of the above mentioned sand-clay mixtures are wetted to a point slightly above field capacity, thoroughly kneaded with the hand and then placed in the permeameters, Table 21 shows the results.

TABLE 21. Hydraulic conductivity (m/d) of artificial mixtures of sand and illite clay (0.0–0.5 mm; clay kneaded), determined by the laboratory permeameter method.

U figure of sand	Percentage kneaded clay aggreates added			
	0	3	6	12
43	17.0	6.5	2.7	0.19
120	2.1	0.44	0.14	0.05
205	1.12	0.28	0.06	0.05

It is clearly indicated from this table, that the harmful influence of a certain clay content on conductivity is very great when the clay aggregates have got the opportunity to adapt their shape to that of the primary pores. With the finest sand, the addition of 3% clay aggregates reduced the conductivity to about a quarter of its initial value and the addition of 12% to one twentieth. In all clay classes of these kneaded mixtures the influence of the texture of the sand is still recognizable; the conductivity is the higher, the coarser the sand.

After all, surveying the whole series of experiments, it appears that the addition of clay has a harmful influence on conductivity. The magnitude of this influence depends on the way the clay is mixed with the sand and is particularly great when the form of the clay aggregates is well adapted to the shape of the primary pores, which case resembles natural conditions. But even in the last case, additions up to 12 percent clay aggregates are not able to offset the influence of the coarseness of the sand on the conductivity.

Results of some experiments with montmorillonite clay

The dominant type of clay of the soil in the Netherlands is the illite. Nevertheless, some determinations of conductivity with montmorillonite have been carried out; this was done mainly to stress the fact that the results of the investigations in this thesis, especially those concerning the natural samples, can only be applied to sediments that are completely comparable with the ones under study.

The sample of montmorillonite used in the investigations was a Wyoming clay with an exchange capacity of 98 m.e./100 gram; the exchangeable cations consisted mainly of calcium. The clay contained practically no calcium sulphate and the calcium carbonate content was less than 0.1 %. Once again the clay sample was dried, ground and separated into two fractions; in table 22 the results obtained with the coarse fraction are shown.

TABLE 22. Hydraulic conductivity (m/d) of artificial mixtures of sand and montmorillonite clay (0.5–1 mm), determined by the laboratory permeameter method.

U figure of sand	Percentage clay aggregates added					
	Permeameter tapped					Permeameter not tapped
	0	3	6	9	12	12
43	17.7	7.8	4.0	0.80	0.29	0.76
120	2.7	0.78	0.56	0.42	0.16	—
205	1.21	0.70	0.50	0.29	0.21	0.00

In contrast with the illite clay, the coarse fraction of the montmorillonite clay had a very harmful influence on conductivity. Adding 12% clay aggregates to the coarse sand effected a decrease of conductivity to about 1/60 of its initial value. This is caused by the particular properties of the montmorillonite clay which, when it is brought in wet conditions, absorbs a lot of water, swells and reaches the upper limit of plasticity. The swelling effects an enlargement of the volume of the soil column: for example adding 3% montmorillonite clay aggregates to the U 205 sample caused an increase of 5% in the volume of the soil column, while with the same percentage of illite clay, practically no increase of the soil volume took place.

From the considerable decrease of conductivity it appears that the swelling of the clay aggregates not only pushed the sand up, but that also the clay was pressed or puddled into the primary pores of the sand. It is, however, possible that this process was affected by the practice of dropping the soil columns repeatedly to attain a standardized packing (see page 28). For this reason an experiment was carried out in which dry mixtures of sand and clay were simply saturated with water and then placed in the permeameters. The results of this experiment are also shown in table 22.

This experiment indicates that also without mechanical influence the coarse montmorillonite clay has a very harmful effect on conductivity. This suggests that in natural conditions montmorillonite, when it swells by the rainfall, can penetrate the primary pores of the sand skeleton whereas illite particles, as was proven by the experiment of table 16, keep stable.

The influence of the fine fraction of the montmorillonite clay was also investigated and the results are given in table 23.

TABLE 23. Hydraulic conductivity (m/d) of artificial mixtures of sand and montmorillonite clay (0.0–0.5 mm), determined by the laboratory permeameter method.

U figure of sand	Percentage clay aggregates added			
	0	1	2	3
43	17.7	6.4	1.90	0.23
120	2.7	1.30	0.39	0.04
205	1.21	0.82	0.27	0.03

The remarkable result is that a very small addition of the fine fraction of montmorillonite has already a fatal influence on the conductivity. An addition of only 3% clay aggregates reduced the conductivity to a small percentage of that of pure sands. It is not possible to compare these results with those of the illite clay because it is not known whether the fineness of the clay aggregates of the illite and montmorillonite clays were of the same order.

MICROSCOPIC EXAMINATION OF SOME ARTIFICIAL MIXTURES OF SAND AND CLAY

In order to obtain supplementary evidence concerning the influence of clay aggregates (illite) on conductivity of artificial sand and clay mixtures, slides were made of 12 selected samples.

After the filling of permeameters with the different mixtures by the method mentioned in page 26, the samples were wetted and allowed to slip from the permeameters (unscrewing the bottom cover) on a cardboard box*. They were then air-dried and impregnated with a mixture of cellulose varnish and acetone (1:1) for two weeks, in order to stabilize more or less the loose samples. The samples were then impregnated with fluid plastic (Vestopal-H) in vacuum for one day and then left for about six weeks in a fume-chamber after which time they were obviously jellied. Thereafter they were oven dried at 40°C for a few days until they were hardened enough to be cut into thin slides (15 μ).

In these slides the percentages of different pore sizes were counted. By using a special ocular (Zeiss integration ocular 1), 25 points appeared in the field under the microscope with a certain distribution pattern. According to the magnification used, the distance between each two points amounts to a certain length in microns. This facili-

* The detailed method of making slides will be published in 1961 by *Dr. Jongerius*, head of the Micropedological Department of the Institute of Soil Survey-Wageningen.

tates the measuring of the pore sizes. To cover the whole slide, one has to count many times; in each slide 2000 points were counted and the sizes of the pores were determined.

Some difficulties naturally arose in the application of this new and comparatively untried method, the most important of which was that the magnification used for the first measurements was not sufficient to detect all the pores of the finer samples and particularly not if the clay content was high. This error was revealed by the very low values obtained for the porosities counted under the microscope as compared with those calculated from the apparent density. Therefore the magnification used was shifted to 400 (8×50).

From the results of these measurements, shown in table 24, it is seen that in the samples without clay or with little clay, the measured porosities under the microscope are in good agreement with the actual ones. When the samples contain more clay, however, the porosity as determined by microscopic examination is rather lower, the reason being that the clay aggregates contain submicroscopic pores which could not be counted. This, however, may be no disadvantage in practice as the submicroscopic pores in the clay aggregates do not appreciably affect water movement.

It appears from the results given in table 24, that with the coarsest sand the added clay aggregates mainly filled up the big pores. Because these pores are very important for conductivity (the water movement per cm^2 is directly proportional to the square of the pore diameter), it can be understood now why the addition of clay aggregates caused such an enormous decrease in conductivity of the coarser sands. Since an increase in the percentage of the smaller pores ($< 50\mu$) has taken place, it is probable that the big pores were not totally blocked but were only reduced in their conducting area. The table also indicates that even an addition of as little as 6% clay aggregates resulted in the disappearance of practically all the big pores. This is in agreement with the previous statement that the influence of clay on conductivity becomes relatively smaller as the quantity added becomes greater.

The reduction in the number of the biggest pores (50–30μ) in the finest sand did not take place at the same rate as in the coarse sand, apparently because the clay aggregates were too big to fit into these pores. As the biggest pores here were blocked less than those in the coarser sand, it can be understood now why the clay addition had a less harmful influence on conductivity on the finer than on the coarser sand.

Thus a good qualitative agreement was found between the results obtained with the microscopic counts and those from conductivity determinations, and it is of interest to consider whether a quantitative relationship can exist between the results of the two methods.

With a certain hydraulic gradient, the quantity of water flowing through a pore is proportional to the fourth power of the pore diameter (d). Further, when a cross section of 1 cm^2 is considered, the contribution of all the pores of a certain class to the water movement is proportional to the number of these pores (n). The contribution of every pore class to the total water movement is thus proportional to nd^4 or to $nd^2 \times d^2$ where nd^2 is proportional to the surface per cm^2 cross section of a certain pore class (= O). The total water movement is thus proportional to the sum of the products

TABLE 24. Distribution of pore sizes in some artificial mixtures of sand and clay, hydraulic conductivity, hydraulic cross section and porosity.

U figure of sand and % clay	K (m/d)	Pores 300-200 µ in vol. %	Pores 200-100 µ in vol. %	Pores 100-50 µ in vol. %	Pores 50-30 µ in vol. %	Pores 30-15 µ in vol. %	Pores < 15 µ in vol. %	Total porosity microscopic in vol. %	Total porosity computed in vol. %	Hydraulic cross section
43–0	17.7	2.86	9.40	14.40	3.40	3.20		33.26	32.70	448000
43–3	10.2	1.15	5.25	9.75	8.20	9.40		33.75	34.00	260078
43–6	4.9	0.04	3.20	7.00	10.70	10.50		31.44	33.70	133000
43–12	1.33	—	0.90	6.30	9.10	13.20		29.50	34.00	73000
120–0	2.7	—	0.60	5.90	15.50	12.60		34.60	38.00	74600
120–3	1.98	—	—	2.10	11.50	22.70		36.30	38.10	34319
120–6	1.23	—	—	1.40	8,70	27.20		37.30	38.60	27800
120–12	0.52	—	—	0.60	7.10	28.80		36.50	40.10	19800
205–0	1.21	—	—	0.50	7.60	13.90	16.90	38.90	39.60	25000
205–3	1.02	—	—	0.30	6.70	10.90	20.40	38.30	40.10	17798
205–6	0.77	—	—	—	5.20	9.70	21.90	36.80	41.20	14200
205–12	0.39	—	—	—	3.20	8.70	26.40	38.30	42.20	9800

Od^2 for all pore size classes ($= \Sigma Od^2$). This total water movement is again proportional to the conductivity. So, a relationship most probably exists between the conductivity and this factor ΣOd^2, which may be called the 'hydraulic cross section'.

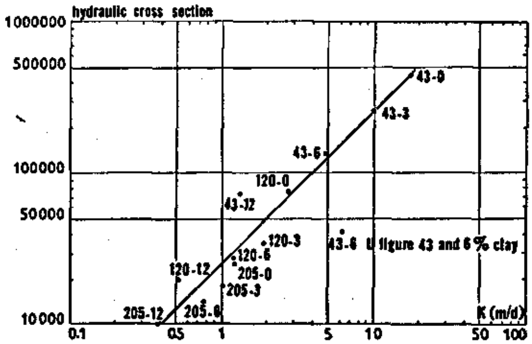

FIG. 8. Relationship between hydraulic cross section and hydraulic conductivity of artificial mixtures of sand and clay, with varying U figures and clay contents.

Fig. 8 shows the relationship found for the different samples between the determined microscopic hydraulic cross section and the conductivity. It can be seen from the figure that there is a close quantitative relationship between the conductivity and the number and size of pores which are counted under the microscope. It also appears from a comparison of the conductivity of e.g. sample 205–0 (K = 1.2 m/d) with that of 120–6 (K = 1.2 m/d) or of the sample 120–12 (K = 0.52 m/d) with that of 205–6 (K = 0.77 m/d), (these samples having a similar hydraulic cross section as well as a similar conductivity) that the clay aggregates have no specific influence on conductivity beyond that of their effect on pore size.

As it appeared now that a quantitative relationship exists between the conductivity and the pore size distribution determined under the microscope, the question arises whether the conductivity could be also calculated from this pore distribution on the basis of Poiseuille's law. Such a calculation has been made but the values obtained were very high. It is probable that the friction in soil capillaries is much greater than in smoother cylindrical capillaries having the same cross section. Further it is also probable that the 'tortuosity' of the water flow is much greater than $\sqrt{2}$, the value given by Carman.

IV. THE CONDUCTIVITY OF NATURAL SOILS

Some remarks on the soils investigated

Most of the samples and profiles investigated in this study originated from the Zuiderzee polders; these soils were deposited under water and are from marine or brackish-lacustrine origin. Some mention of the relative proportions of clay, silt, organic matter and calcium carbonate in these soils has already been made in chapter II. These Zuiderzee polders exhibit the greatest variation of all Dutch marine soils in their ratios of clay content to sand fineness and therefore they offer representative examples for this study.

The Zuiderzee polders were drained only 30 years ago and the effects of soil formation processess in the classical sense (e.g. podsolization or cementation) are still of no importance. The evidence that the deposits have undergone very little change since they were drained is particularly clear in the deeper layers. This is also the case in all Dutch marine soils. It is therefore likely that the conductivity of other Dutch marine soils which tend to have a similar granular composition does not differ to any large extent from that of the Zuiderzee polders.

Because the Zuiderzee polders were deposited in brackish water, their adsorption complex contained about 15% exchangeable sodium at the time of draining. Gypsum was formed afterwards in the soil (by oxidation of sulphides and reaction with calcium carbonate) and it can be accepted that the exchangeable sodium at the time of this study would already have been replaced by calcium or at least would not be present in sufficient quantities to exercise a harmful influence on conductivity.

The granular composition

In the last chapter it appeared that the conductivity of sandy soils depends on the composition of the sand fraction, the porosity and the clay content. All possible combinations of clay content, porosity and sand composition can be made with artificial samples but in nature these factors are interrelated with each other to a greater or lesser extent. To interpret the data obtained from natural soils, it is desirable to deal beforehand with these interrelations.

Marine soils are transported and deposited by streaming water and the stronger the stream the bigger the particles transported. Thus every stream of water carries with it a whole assortment of particles of different sizes, the maximum size of which is determined by the velocity of the current. As soon as the velocity decreases the coarse particles settle down.

Sedimentation circumstances vary in the course of time and so the size of the particles deposited in any one place differs accordingly. Conditions for sedimentation can change so much and so irregularly that the particle composition becomes very unpredictable. Usually, however, this is not the case in marine and similar sediments;

sedimentation circumstances tend to fluctuate around a certain equilibrium state. This is seen from the fact that the composition of most sands is of a Gaussian type: one of the subfractions being the most frequently met with and the coarser and the finer subfractions decreasing in importance as they diverge more from this size of grains.

Thus if one sand is finer than another it does not necessarily mean that a certain fine fraction appears more in the one case than in the other or that the other subfractions are distributed evenly or arbitrarily, but it does mean that the whole granular composition is shifted to the finer side. Table 25 shows the granular composition of 6 sands of increasing fineness. These sands which belong to the series discussed in chapter III were obtained from natural sandy soils from which the clay had been washed out. Some of the finest subfractions were naturally lost in this washing but this loss was not sufficient to cause radical changes in the sand composition. The Gaussian distribution of the sand composition of all samples and the gradual progressive shifting of the main subfraction to the left hand as the whole composition becomes finer can be easily seen from this table.

TABLE 25. Composition of six marine sands increasing in fineness.

No. of sand	% subfraction (in mu)											U-figure of sand
	0.016–0.050	0.050–0.075	0.075–0.105	0.105–0.150	0.150–0.210	0.210–0.300	0.300–0.420	0.420–0.600	0.600–0.85	0.85–1.4	1.4–2.0	
1	0.1	0.6	0.6	1.0	1.9	13.5	45.2	29.6	5.8	1.4	0.3	29
2	0.1	0.2	0.3	2.5	50.5	42.0	3.8	0.5	0.1	0	0	49
3	3.9	8.9	24.9	45.8	10.4	2.2	1.7	1.3	0.6	0.2	0.1	102
4	9.0	22.7	36.5	25.1	3.5	0.8	0.7	0.7	0.6	0.3	0.1	136
5	17.5	36.3	35.7	8.5	0.9	0.6	0.2	0.2	0.1	0	0	175
6	56.4	39.9	1.6	0.6	0.8	0.5	0.1	0.1	0	0	0	278

Further analysis of this Gaussian-distribution reveals that the composition of most marine and similar sands obeys certain laws. In fig. 9 the 'median' value (the particle diameter which occurs halfway along the accumulative distribution curve) is plotted against both quartile values (particle diameters which occur respectively at quarter and three quarters along the accumulative distribution curve) for the 43 sands which are discussed in chaper III. The quartile values of all sands are very narrowly clustered around the lines drawn.

Clay can also be deposited by the streaming water and, as was already mentioned several times, this clay is not found in separate particles but in aggregates. Their 'hydraulic value' is such that their chances of being deposited are of the same order as those of the finest subfractions of sand. Thus as the current velocity decreases clay aggregates become deposited together with the finer sand. This means that there exists a correlation between the clay content and the sand composition. For certain types of sediments this correlation is very strong as appears from fig. 10 which gives

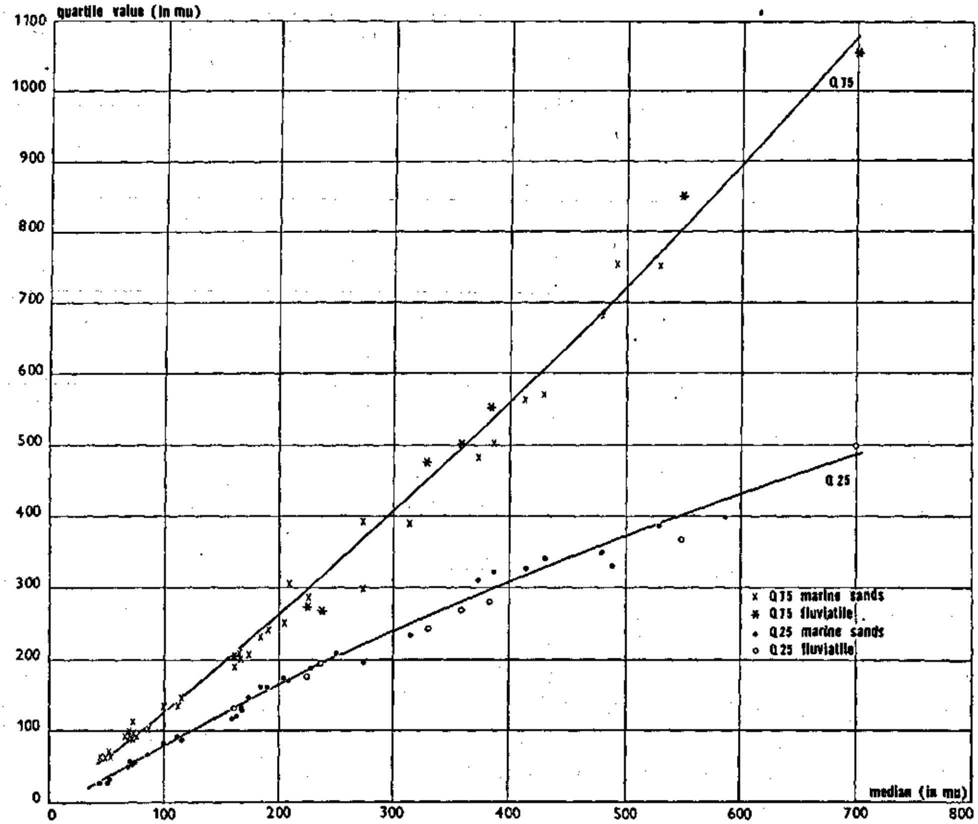

FIG. 9. Relationship between quartile values and median.

the relationship between the clay content and the U figure (this as a measure of the fineness of sand) of a number of samples deposited in the 'Dollard'.

The relationship between the sand composition and the clay content is unfortunately not always the same. Perhaps the sizes of the clay aggregates and consequently the opportunities for sedimentation differ from place to place and a different aggregate size results naturally in a different relationship between clay content and sand composition. Furthermore, the sedimentation circumstances can alter in the course of time. If these alterations are large, at high velocities of the current, coarse sand can be brought down and settle afterwards; this leads to another relationship between clay content and composition of the sand.

The main factor in the variations in this relationship between clay content and sand composition in connection with the marine deposits under study is, however, the size of the sand particles available for sedimentation. If the water by means of which sedimentation takes place contains only very fine sand, then the relationship between clay content and sand composition will shift more towards a higher proportion of the fine sand than if coarser sand particles were also available for sedimentation.

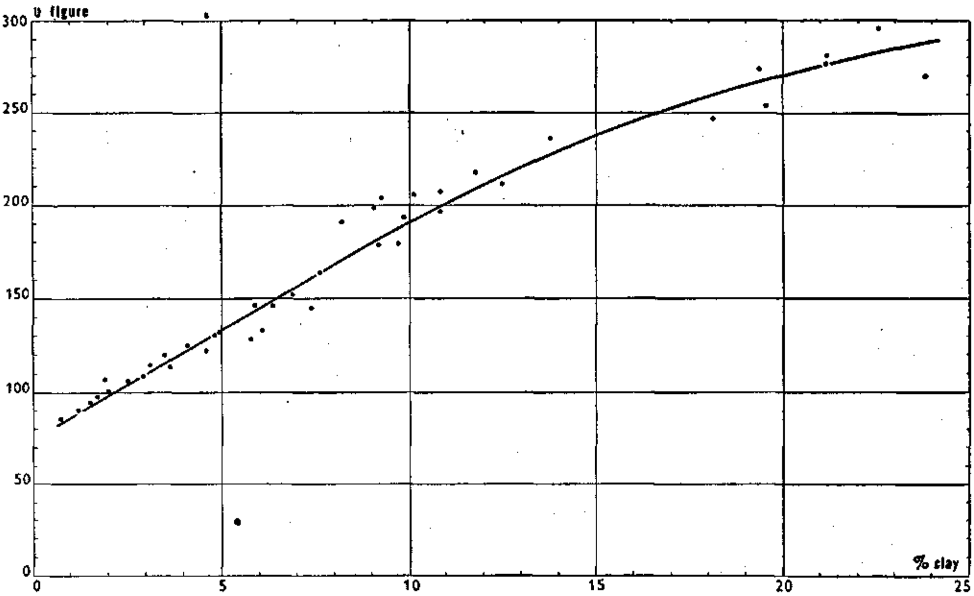

FIG. 10. Relationship between U figure and clay content for 'Dollard' soils.

Regional differences in particle size of the sand present in the streaming water are indeed found in the Dutch marine sedimentation milieu. This, together with the other reasons, leads to the fact that the relationship between clay content and sand composition is not always found to be the same. Of course, it is impossible to find in coarser sands a high clay content (at least if the circumstances remained about the same during the sedimentation process), but it is possible to find both high and low clay contents in fine sands.

THE POROSITY

In considering the relationship between porosity and granular composition the sand composition and the clay content have to be dealt with separately. To begin with, it can be stated that porosity could be independent to a certain degree of the particle size of the sand. If one starts with n spherical particles of the same size (radius r) and array (for exemple cubical) then the volume of the particles themselves is $n\ 4/3\ \pi\ r^3$ and the total volume occupied by the system is $n\ 8\ r^3$. The porosity is then:

$$\frac{n\ 8\ r^3 - n\ \frac{4}{3}\ \pi\ r^3}{n\ 8\ r^3} = 1 - \frac{1}{6}\ \pi$$

and thus independent of the particle size. This applies also to other packings. Even with sands of varied composition in which part of the smaller particles occur in the spaces between the bigger ones, the porosity could be independent from the size of the grains, provided the distribution curves of the sands are similar.

On the other hand, the number of contact points between the particles per unit volume is greater for the finer particles than for the coarser, and thus the friction is increased and also the resistance against close packing. In conductivity determinations carried out for disturbed sands without clay, it appears that other circumstances being equal, the porosity increases as the fineness of the sand increases. Hooghoudt's results which were obtained in the previously mentioned investigation are very illuminating as can be seen in table 26.

TABLE 26. U figure of sand subfractions and porosity by standardized packing in a permeameter

Diameter of sand subfraction (in mu)	U figure of sand subfraction	Porosity (as part of total volume)
16– 43	397	0.432
43– 74	180	0.426
74–104	115	0.403
104–147	81	0.378
147–208	57	0.368
208–295	41	0.364
295–417	27	0.361

As to the relationship between clay content and porosity, the clay particles are found in aggregates and these aggregates are, in contrast to the sand particles, not massive but porous. Increase of clay content means to a certain extent replacement of sand grains by clay aggregates and thus an increase of porosity.

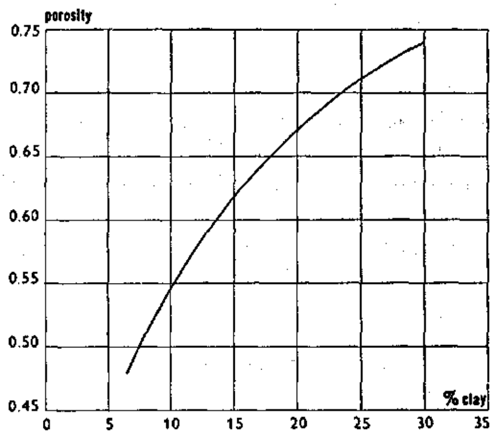

FIG. 11. Relationship between porosity (as part of total volume) and clay content of recently drained Zuiderzee soils.

The magnitude by which the porosity increases due to addition of clay depends on two factors: first the amount of clay aggregates stored in the pore spaces present between the sand particles (especially this is the case in sandy soils) and second the porosity of the clay aggregates themselves. If the clay aggregates are recently deposited, their structure is very loose and their porosity is very high. Consequently, the porosity of marine sediments recently deposited increases highly with the increase of clay content (see fig. 11). After bringing the soil under cultivation, however, forces of capillary tension appear, and this leads to loss of water and shrinkage of the loose structure of the clay aggregates. Thus the porosity of the clay aggregates decreases and also their influence on the total porosity of the soil. This process is of great importance to the upper layers but much less to layers lying just above or beneath the ground water table.

At the same time the undisturbed cores were taken, other rings were also placed in the field for porosity determinations. A summary of the results obtained is shown in table 27 where the porosity of 39 samples is classified according to clay content and U figure.

TABLE 27. Porosity of 39 natural marine sandy soils, lying just above the ground water table, classified according to clay content and U figure. (Porosity as part of total volume).

% clay class	U figure class			
	30–60	60–100	100–200	> 200
> 5			0.53, 0.54, 0.54, 0.59,	0.49, 0.50, 0.52, 0.53, 0.54
2.5–5		0.44, 0.46	0.40, 0.40, 0.41, 0.41, 0.41,	0.42, 0.42, 0.45, 0.45, 0.51
0.0–2.5	0.37, 0.37, 0.38, 0.38, 0.40, 0.41	0.38, 0.40, 0.42, 0.42,	0.35, 0.37, 0.39, 0.42, 0.45	0.42, 0.43. 0.46

The porosity of sandy samples appears to increase with the increase of clay content. Even in sands having very low clay content the clay aggregates are not totally stored in the pore spaces existing between the sand particles. It appears from comparing the samples of clay class of 0–2.5% with those of 2.5–5%, that the average clay content and the porosity are respectively 1.4% and 0.019 higher in the latter than in the former. From all the data in this table, it can be generally accepted that the porosity increases with 0.015 per 1% clay.

TABLE 28. Frequency of porosity in natural marine sandy soils, just above the ground water table calculated on a clay-free basis.

Porosity as part of total volume	U figure class			
	30–60	60–100	100–200	> 200
0.32–0.34			1	
0.34–0.36	1		3	
0.36–0.38	2	2	5	2
0.38–0.40	2	3	1	2
0.40–0.42		1		
0.42–0.44			1	

The influence of sand fineness on porosity is small compared with that of clay content. In table 28 the porosities of samples with clay content less than 5% are given whereby per 1% clay the porosity was reduced by 0.015.

The porosity is chiefly important because in pure sands it is positively correlated with conductivity. However, it is likely that the increase in porosity caused by increase in clay content does not affect conductivity; the pores in the clay aggregates are so small that they contribute practically nothing to the water movement. Therefore, it is certainly not permissible to calculate the conductivity of natural soils containing some clay from the U figure by the formula given on page 50.

From the figures in table 28 it seems that no definite correlation exists between porosity and U figure. While the average porosity of sands (calculated on clay- free basis) for all the U figure classes is 0.38, it is obvious that some of them rather deviate from this average. These variations could be partly attributed to the different ways in which sedimentation took place. However, judging from the considerable differences which existed in the porosities of duplicate samples taken at very short distances apart, it could be that these differences were to a large extent accidental.

The following table shows the correlation between porosity and the factor $\frac{p^3}{(1-p)^2}$ or in other words between porosity and conductivity (calculated).

TABLE 29. Values of the factor $\frac{p^3}{(1-p)^2}$ with different porosities.

Porosity (as part of total volume)	$\frac{p^3}{(1-p)^2}$	Relative value of $\frac{p^3}{(1-p)^2}$; p 0,38 = 100
0.34	0.09	64
0.36	0.11	79
0.38	0.14	100
0.40	0.18	128
0.42	0.22	157
0.44	0.27	193

It appears from these figures that the porosities of three quarters of the sandy samples, calculated on a clay-free basis, deviated from the average value of 0.38 by less than 0.02. This difference of 0.02 amounts to a deviation of about 25% in conductivity terms and is of the same order of magnitude as the random deviation. Since it appeared to bear no relationship to any property of the profile or the composition of the soil, it can probably be accepted as being within the limits of experimental error.*

* After completion of this research some measurements were carried out to estimate the conductivity of older soils of diluvial origin. Though the porosity was rather lower in these soils (somewhat more than 0.30, calculated on a clay-free basis) the conductivity was, with the same U figure and clay content, about the same. In a later paragraph it will be shown that the formula of page 50 is not applicable to natural soils and the reason may be that the influence of porosity on conductivity of natural soils is less than for pure disturbed sands. In any case, the results support the supposition that the porosity can be considered as a factor, playing only a minor role in the conductivity of natural marine sands.

THE SIGNIFICANCE OF PATTERNS OF POROSITY AND OF DISTRIBUTION OF GRANULAR COMPOSITION IN CONDUCTIVITY INVESTIGATIONS

It appears from the last sections that the composition of marine sands follows a certain law and thus one parameter is sufficient to characterize the whole sand composition. This parameter can be, as stated earlier, the median or the U figure and indeed a rather close relationship exists between the two parameters as seen in fig. 12. Thus it might indeed be possible to develop also a formula for the relationship between conductivity and median. Similarly, a correlation exists between the conductivity and Hazen's effective size and it can be understood now why such a parameter, which is in itself of little significance, can be useful in a conductivity formula.

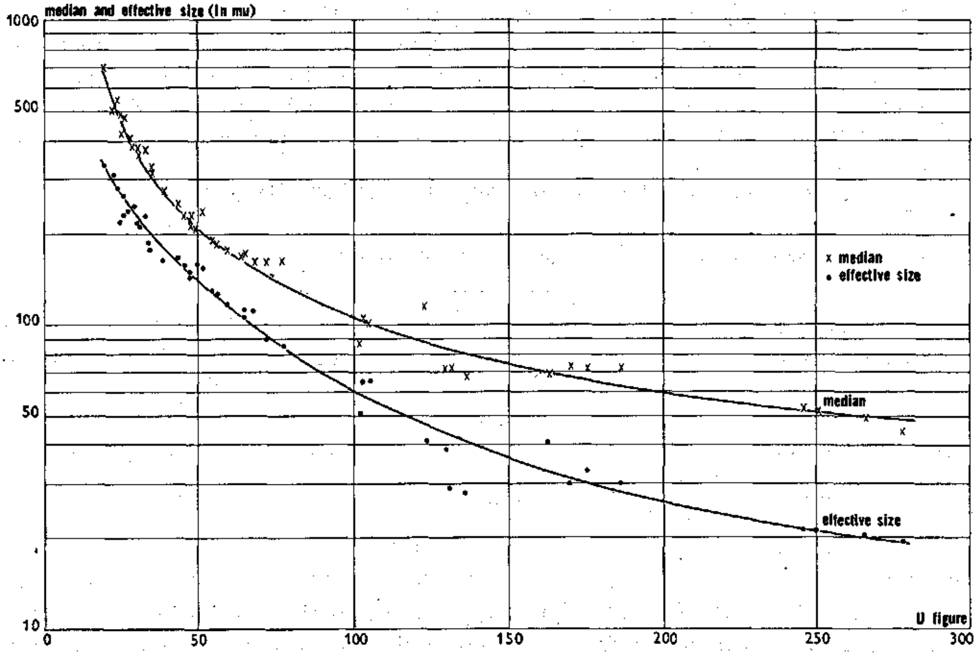

FIG. 12. Relationship between median, Hazen's effective size and U figure.

Perhaps the most important fact regarding the relationship between particle size of sand and the clay content is that the number of possible combinations of the two is limited and that in natural homogeneous marine soils, coarse sand is never associated with high clay content.

It appeared from the last section that the porosity, on a clay-free basis, is approximately constant for the sandy soils and the value can be taken as being about 0.38. Thus it is a little higher than HOOGHOUDT's value on which he based his calculations (HOOGHOUDT, 1934). With the increase of clay content the porosity increases, but this increase is of no importance in questions of conductivity. For this investigation where a relationship between the particle size and clay content is sought, the porosity does not play a role as a separate factor.

It is also obvious that the formulas, which give the relationship between particle size and conductivity and in which the porosity is not included separately, can give good results for certain sands free from clay.

THE AIR CONTENT

Artificial samples investigated in the laboratory were freed from air and thus the influence of air on conductivity was eliminated. Natural soils, however, can contain air.

IRMAY (1954) developed a formula in which he expressed the effect of air on conductivity as follows:

$$\frac{K_1}{K} = \frac{(S - S_0)^3}{(1 - S_0)^3}$$

K = conductivity of saturated soil,
K_1 = conductivity of soil containing air,
S = the part of the pores occupied by water and
S_0 = the part of the pores occupied by water not contributing to the flow.

If the air content is not high, the influence of the term S_0 will be negligible. Assuming this, the effect of air content present in the soil is as given in table 30 (the calculation is based on a porosity of 0.40).

TABLE 30. Relationship between air content and hydraulic conductivity (according to IRMAY).

Air content (in vol. %)	Relative hydraulic conductivity (K at air content 0 = 100)
0	100
2	86
4	73
6	61
8	51
10	42

From this table it appears that even a small quantity of air can cause effective reduction in conductivity. Probably, this is analogous to the phenomenon, whereby a small addition of clay in artificial samples of clay and sand effected a great decrease in conductivity (see table 19); the clay aggregates (or in this case air bubbles) find their place mainly in the bigger pores which contribute most to the water movement. In analogy with the case of clay additions, it might be concluded that air content does not exercise the same influence on conductivity for all sands but has a greater effect in coarser sands.

In the samples, dealt with in the previous section, the air content was determined in addition to porosity. It is worthwhile to remember that these samples were taken mainly from just above the ground water table except in a few instances where the required sand composition could not be obtained in this region.

From the 43 spots investigated, 35 of them were either totally or practically free from air (less than 2.5% air; the determination is not very accurate). At least 3 of the other 8 were most probably taken at considerable height above the ground water table (the ground water table itself was not recorded at the sampling), while the other 4 (the eighth sample will be discussed later) were very low in their U figure (thus with little capillary rise) and were taken 20 cm higher than the air-free samples with the same U figure.

These results tend to indicate that the air is most probably absent in the investigated soils just above – and also beneath – the ground water table. Thus in the deeper layers which are the most important for water movement, air should not be considered as an important factor. Some restrictions, however, have to be added. The investigated soils were at most about 20 years old. The possibility exists that in older soils air content could be higher either through evolution from the penetrating water or if the ground water table had at any time sunk to a very low level, through replacement of water in the deeper layers by air which remained entrapped. This might be indicated by the somewhat higher air content (4%) found in a spot originating from a 30 years old polder, though this sample was taken near the ground water table.

In spite of the tendency indicated by these results that air should not be viewed as an important factor for the water movement in the field, the fact remains that eight of the undisturbed cores in the investigated spots contained air; experiments indicated that this air was not expelled during the measurements. The air content of five out of those eight samples ranged from 4–6%; in two cases it amounted to 8% which, according to table 30, means an approximate reduction of one third to one half of the conductivity.

Hydraulic conductivity of undisturbed cores in vertical and horizontal direction

In the auger hole and drain-discharge methods the determination of conductivity is mainly carried out in a horizontal direction, but in the field permeameter method it can be also determined vertically. Therefore to find whether differences in values exist in both directions, in some layers investigated by the field permeameter method half of the samples was taken horizontally while the other half was taken vertically. The results of the measurements in two directions are compared in table 31 and it is worthwhile to mention that although the spots were chosen with the utmost care, completely satisfactory spots could not always be found. Therefore, after the measurements, soil cylinders were dried and soil cores were cut in different directions to get an idea of the extent to which homogenity was lacking or the occurrence of other irregularities.

TABLE 31. Ratio of horizontal to vertical hydraulic conductivity of undisturbed cores, determined by the field permeameter method.

	K hor. : K vert.				
	< 0.8	0.8–1.1	1.1–1.4	1.4–1.7	> 1.7
Number of spots for every class	3	4	5	7	4

The horizontal conductivity from 3 sites out of the 23 was considerably less than the vertical ($K_{hor.} : K_{vert.} = 0.6$ till 0.7); in 2 cases this could be attributed to the occurence of channels of old roots in the vertical cores. On the other hand, there were four cases in which K_{vert} was remarkably less than $K_{hor.}$. In one case ($K_{hor.} : K_{vert.} = 1.8$) the cores contained some shells lying horizontally in the ground. In 2 cases, ($K_{hor.} : K_{vert.} = 5.6$ till 6.3) the sand contained one or more very thin but rather pronounced clay layers; this was already known before placing the cylinders.

In the biggest group, with ratios $K_{hor.} : K_{vert.} = 1.4–1.7$, the impression got while inserting the cylinders in the profile, was that the soil was fairly homogeneous. However after drying the samples, when the structure of the soil can be better ascertained some layering was also observed in the cores of this group; both finer and coarser layers as well as layers containing somewhat more organic matter occurred.

In the group with $K_{hor.} : K_{vert.} = 0.8–1.4$ channels of roots and layers were both absent or their presence was so little that they hardly excercised any influence on conductivity.

It appears from this study that even the soils considered as homogeneous at first sight are often layered and in such cases the horizontal conductivity is greater than the vertical. The horizontal conductivity, however, is more important than the vertical because the water movement in the soil is mainly horizontal and the clayey layers are not sufficiently impermeable or continuous to impede totally water movement or to require a high pressure head. Fortunately with the auger hole and the drain discharge methods the conductivity is determined in horizontal direction. As a consequence of the results of this investigation, the data of the field permeameter method, determined in vertical direction, have been discarded and discussions in the later sections are based entirely on conductivity obtained in a horizontal direction.

CALCULATION OF HYDRAULIC CONDUCTIVITY OF NATURAL SANDY SOILS FROM THE U FIGURE

The conductivity of natural soils, even when the clay content is very low, is much less than that calculated by the formula on page 50, as will be shown later on in this section. A possible explanation could be that in undisturbed cores the particle arrangement is more unfavourable than in disturbed and to test this the conductivity of some sandy soils was determined by the laboratory permeameter method in several different ways:

A. the samples were first homogeneized and then placed in the permeameters in their natural wet condition. Thereafter they were handled in the normal way (see page 28);
B. the same except that the samples were firstly dried;
C. the same except that the samples were freed from clay by washing and then dried.

Usually the samples are placed in the permeameters in a dry condition and then evacuated and saturated. It was doubtful whether air could be eliminated from samples filled in the natural wet condition, but it appeared from checks made after conductivity measurements that in fact all the samples were air-free. The results of the investigation are shown in table 32. Because the porosity of the samples differed and the U figure was lowered a bit by washing, the conductivity is not given in the table but the μ-factor, calculated from the conductivity, is given instead. (The porosity and air content of the coarsest sample were not determined. In analogy with the results of other samples it could be accepted that this sample was also free from air after saturation. The porosity was guessed but an error in this estimate would not have much influence on the results).

TABLE 32. Value of the factor μ in disturbed samples pretreated in different ways and investigated by the laboratory permeameter method.

Way of pretreatment and filling	U figure of sand and % clay		
	65–2.6	136–2.3	163–2.5
A. Soil homogeneized and filled in field wet condition	6×10^4	6×10^4	9×10^4
B. Soil dried, homogeneized and filled in a dry condition	13×10^4	18×10^4	17×10^4
C. Soil washed, dried, homogenized and filled in a dry condition	18×10^4	19×10^4	20×10^4

From this table it can be seen that the μ-factor is much higher in sands freed from clay than in the original soils containing their natural low clay content. If other conditions are the same, the conductivity of sands freed from clay is about two times as much as that of natural sands, even when their clay content is very low. It is remarkable that drying of the soil has about the same effect as removing the clay.

The interpretation of these results for the study of the relationship between clay content and conductivity will be dealt with in another section; here the discussion will be limited to the methodical consequences of this investigation. The determination of the factor μ in washed sands or in pure subfractions may be of importance for calculations and considerations of the relationship between particle size and conductivity. Such a factor, however, cannot be applied in the calculation of the conductivity of natural sands, which always contain at least some clay. This conclusion is in opposition to HOOGHOUDT's, who stated that the factor μ, determined with pure subfractions, also holds for the calculation of the conductivity in natural sands containing low clay percentages (HOOGHOUDT, 1934).

From table 32 it can be seen how HOOGHOUDT mistakenly arrived at his conclusion. The factor μ was determined in pure subfractions and he calculated the conductivity of natural sandy soils containing low clay content with this (too high) μ-factor and at the same time he determined the conductivity of these samples to check his calculations. These determinations, however, were carried out, as is usually the case in laboratory investigations, in dried soils, but the conductivity under such conditions is higher than that of natural soils at some depth below the soil surface, which never dry out completely. Consequently both calculated and determined conductivities were too high but the figures relatively fitted each other because both types have the same μ-factor.

Hydraulic conductivity of marine soils, determined by the field permeameter method

The results of these conductivity determinations are plotted in figure 13. The clay content is given for every site and a downward dotted line indicates that the conductivity could have been higher had the cores not contained air; for the samples with less than 5% clay an upward or downward dotted line can also mean that the conductivity could have been higher or lower had the porosity approached the normal value. Finally, for one sample with an abnormally low clay-silt ratio the clay content was raised somewhat. Fig. 13 shows in the first place a line indicating the relationship between conductivity and U figure for sands free from clay at 0.38 porosity; this line being calculated from the formula on page 50.

If the relationship between conductivity on the one hand and U figure and clay content on the other has to be studied, the fact that the range of variations of clay content is very limited in the coarser sands must be born in mind; rather wide range of variation in clay content can only be found in fine sands. The clay content ranged from about ½ till 2% in the coarser sands. Within this very limited range of clay content, it seems to make little difference for conductivity whether this content was ½ or 2%. On the other hand the conductivity of the group as a whole (even of the samples with a very low clay percentage) lies far below that of sands free from clay (thoroughly washed).

With high conductivities ($K > 7$ m/d) the determination of conductivity is rather unreliable. In the range $K = 1$ to 7 m/d most observation points are rather closely clustered around the line drawn; two observations (with 2.4 and 3.8% clay) have a too low conductivity. This may be due to their somewhat higher clay content; one of the samples was moreover an abnormal one (very high $K_{hor.} : K_{vert.}$ value).

The clay content is higher in finer sands; from the results of these sands it is very obvious, that a relationship exists between clay content and conductivity. In the group with about 8–15% clay the conductivity is only a fraction of that in the spots with about 2½–3½% clay. In both groups the observations are clustered rather closely around the line drawn.

Furthermore it is easy to see that the curve of the relationship between conductivity and U figure will flatten out as the clay content becomes higher. At 10% clay the coarseness of the sand skeleton hardly exercises any more influence on conductivity. It

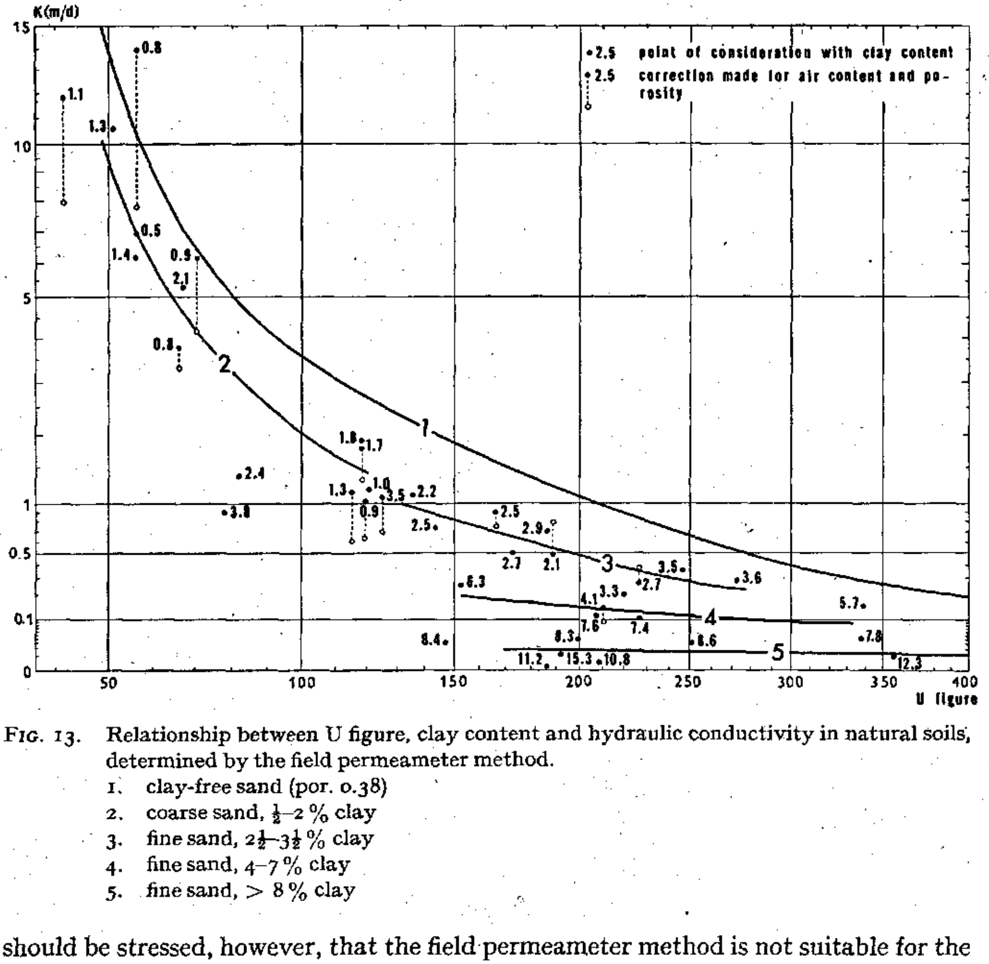

FIG. 13. Relationship between U figure, clay content and hydraulic conductivity in natural soils, determined by the field permeameter method.

1. clay-free sand (por. 0.38)
2. coarse sand, ½–2 % clay
3. fine sand, 2½–3½ % clay
4. fine sand, 4–7 % clay
5. fine sand, > 8 % clay

should be stressed, however, that the field permeameter method is not suitable for the determination of very low conductivities; at these low conductivities leakage between the core and the cylinder wall undoubtedly is relatively important. Thus the conductivity results given in this class have to be considered as maximum values.

The conductivities of a number of soils having clay contents between 4 and 7% lie unmistakebly between both other groups. The variation of conductivity in this group is small in m/d terms but, taken relatively, is rather large. The figures deviate so much from those in the other two, that it seems justifiable to draw a further line through the points.

Figure 13 does not, however, offer a direct quantitative insight into the relationship between conductivity, U figure and clay content, because the axes are not linear. Figure 14 which is better in this respect, shows the relationship between clay content and conductivity for different U figures. The conductivity is expressed in a percentage of the conductivity had the soil been free from clay. The reliability of this figure is rather questionable and it can only give some qualitative indications of the actual relationship. It seems from this figure that the influence of the coarseness of the sand on the relationship between clay content and conductivity is relatively small; one curve might be drawn through the points. Fig. 14 is the most simple one to demonstrate that the clay content has a great influence in reducing conductivity at all U figures; at about 10% clay all the pores are obviously blocked by the clay particles.

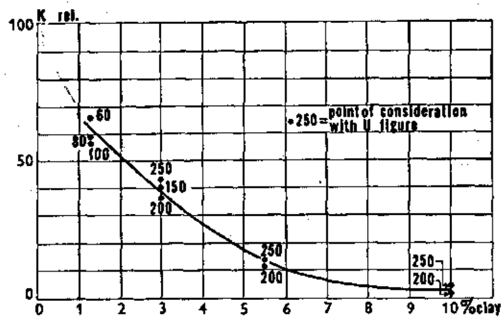

FIG. 14. Relationship between relative hydraulic conductivity (K clay-free sand = 100), U figure and clay content in natural soils.

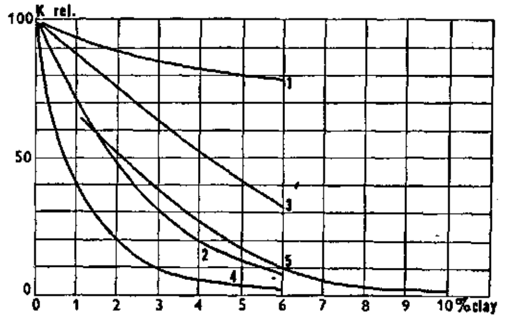

FIG. 15. Relationship between relative hydraulic conductivity (K clay-free sand = 100), U figure and clay content in natural soils.

1. sand U 120, mixed in a dry condition with coarse clay aggregates (½–1 mm)
2. sand U 43, mixed in a dry condition with fine clay aggregates (0–½ mm)
3. sand U 205, mixed in a dry condition with fine clay aggregates (0–½ mm)
4. sand U 43–205, kneaded in a wet condition with fine clay aggregates (0–½ mm)
5. natural soils.

It is of importance to see fig. 14 in the light of the experiments carried out with artificial samples. Therefore the curve of fig. 14 is shown in fig. 15 together with those of some artificial soils, whereby the clay was mixed with sand in different ways. Comparison, however, is only possible on a limited scale because the specific volume of the clay aggregates in natural soils is much greater than that of artificial mixtures and consequently also their influence on conductivity. Some conclusions, however, can be drawn from these figures. The difference between line 1 (sand mixed with coarse clay aggregates in a dry condition) and line 5 (natural soils) again supports the conclusion already mentioned that the clay particles in natural soils do not contribute much to the building up of the porous soil skeleton as in the case with coarse clay aggregates, but that they indeed block the pores between the sand. This blockage is not the maximum possible; when the clay is kneaded with the sand, the detrimental influence on conductivity is much stronger. Line 4 shows that very small quantities of clay can already give a great decrease in conductivity.

When the sand particles are mixed in a dry condition with fine clay aggregates, the U figure has a great influence on the magnitude of the decrease of conductivity caused by the clay. With the coarse sand the shape of the curve is concave, indicating that the biggest pores (which are the most important ones for water movement) are blocked first; with the finest sand the pores are more equally blocked. It seems that the influence of the clay on conductivity in natural soils is more or less similar to that in the coarse sand; the influence of the presence of clay in small amounts is proportionally greater than when it is present in larger quantities.

The question arises how to extrapolate line 5 (natural soils) in fig. 15. The curve could reach the Y-axis at $K_{rel.} = 100$, but the shape suggests also that this is more likely to happen at a lower value. The latter would mean that an essential difference exists between natural soils and washed sands, a supposition also borne out by the fact, that a significant difference could not be detected between samples with ½ or 2% clay. If this is so – but the reliability of figure 15 is far too small for a definitive conclusion – it could be supposed that natural sands are covered with a voluminous crust of clay and organic matter (dead and alive), wh ch tends to increase the roughness of the particles and thus the friction. The fact that conductivity of dried natural samples approached that of the washed samples, is also an indication in this direction; this phenomenon, however, can also be explained in another way (irreversible shrinkage of the clay particles).

HYDRAULIC CONDUCTIVITY OF MARINE SOILS, DETERMINED BY THE AUGER HOLE AND DRAIN DISCHARGE METHOD

As has been already mentioned in chapter II it was not possible to investigate a wide variation of U figure and clay content combinations by these methods; it is therefore meaningless to classify the results obtained according to U figures and clay contents. It seems better to see whether these results fit into the scheme of the field permeameter results. The results, obtained by the auger hole and drain discharge method, are given in figure 16 and 17; in these figures also the lines of figure 13 are shown. A comparison between the results of both methods with those of the field permeameter method is only possible for two groups of soils, namely soils with U figures ranging from about 55 to 90 and having low clay content, and with U figures ranging from 200 to 300 and richer in clay.

As to the first group, the conductivities of the auger hole as well as those of the drain-discharge method are – for the same U figure and clay content – in the same order of magnitude as those of the field permeameter method. The values of the auger hole method are narrowly clustered. They seem to be lower than those of the field

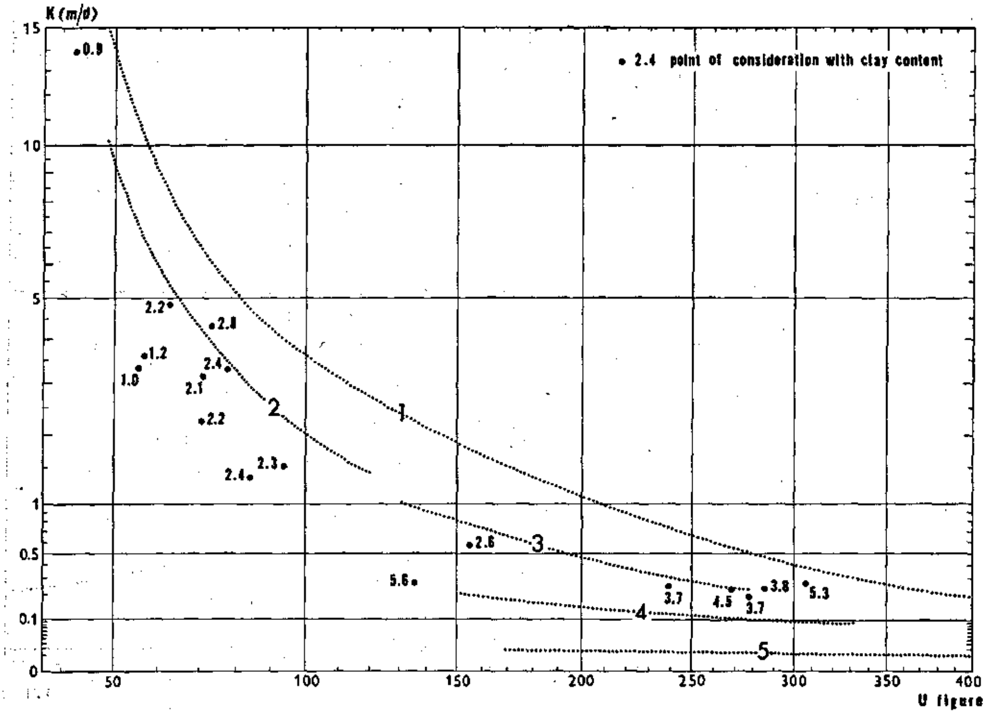

FIG. 16. Values of U figure, clay content and hydraulic conductivity, determined by auger hole method.
1, 2, 3, 4 and 5 relationship determined by field permeameter method (see fig. 13).

permeameter method. The average clay content is indeed somewhat higher (about 2.5%); but it is not out of the question that the two methods yield a slight different picture of conductivity. The average value of the drain discharge method is about the same as that of the field permeameter method. The points show a big variation, possibly due to the many assumptions and corrections necessary for the calculation of the conductivity.

In the finer group the results of the three methods are also of the same order of magnitude. In m/d the differences are often very small; relatively speaking the conductivity, determined by the auger hole and drain discharge methods, is in only some cases rather higher than that obtained with the same clay content by the field permeameter method. This might be partly due to the fact, that with these methods the layers investigated were less homogeneous than with the field permeameter method. The horizontal conductivity of a combination of more and less permeable layers is higher than that of a mixture of both, as the relationship between conductivity on the one hand and both U figure and clay content on the other is concave in fig. 16 and 17.

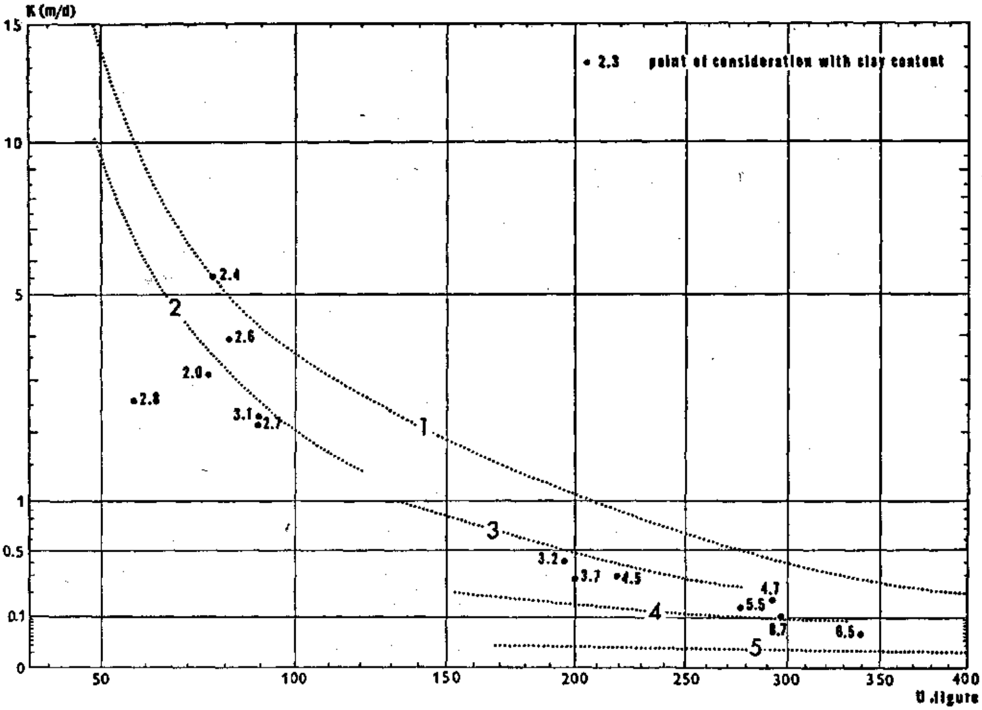

FIG. 17. Values of U figure, clay content and hydraulic conductivity, determined by drain discharge method.
1, 2, 3, 4 and 5 relationship determined by field permeameter method (see fig. 13).

THE RESULTS OF THE FIELD PERMEAMETER, AUGER HOLE AND DRAIN DISCHARGE METHOD, CONSIDERED TOGETHER

It appears from figures 16 and 17 that, generally speaking, there is reasonable agreement between the results of the field permeameter, the auger hole and the drain discharge method. From this it can be concluded that all three methods are able to offer at least a fairly reliable impression on the conductivity of marine sandy soils. Each method has its advantages and limitations and the best view on the conductivity of sandy soils can be got, when the results of the three methods are combined. The broadest picture is given by the field permeameter method, but it is likely that the values of the two other methods, obtained at some points of the whole range, are somewhat more reliable. Thus it seems appropriate to start from the curves, obtained with the field permeameter method, and to gauge them with the results of the auger hole and drain discharge method. The result is shown in table 33.

As seen from the table a relationship exists between the conductivity and the U figure in natural soils, as well as in pure sands, and it is obvious that the clay content excercises a great influence on this relationship. One of the important results of this

TABLE 33. Hydraulic conductivity of homogeneous natural marine sandy soils lying under or near the ground water table. (Conductivity in m/d at 10° C).

U-figure	% clay				
	0 clay-free	½–2	3	5	> 8
50	14	9			
60	9	6			
80	5	3			
100	3.5	2.0			
125	2.6	(1.4)	(1.0)		
150	2.0		0.7		
200	1.2		0.5	0.12	< 0.02
300	0.40		0.20	0.08	< 0.02

study is that the relationship between conductivity, U figure and clay content is quantitatively fixed. As the table is based on extensive and interrelated data it probably gives a reliable picture of the influence of clay content on conductivity.

This does not alter the fact that with the application of this table rather big deviations may be expected, although it is unlikely that they will be as great as the deviations of the separate points in fig. 16 and 17 suggest. Every point in these figures relates only to one observation. In practice a certain area is always considered and its average conductivity has to be estimated; this average will be closer to the curves, drawn in fig. 16 and 17 than the single observations. However, if this table is used for estimating conductivity from granular composition, the deviation between the guessed and the actual conductivity may be about one third or even on occasions one half.

These deviations may seem big, but it has to be born in mind that the conductivity in this type of soil ranges from about 0.015 till 15 m/d; the maximum is about 1000 times bigger than the minimum. In the light of this fact it is certain that the conductivity can be estimated from U figure and clay content with an accuracy, sufficiently high to assist in the solution of a number of problems encountered in the field, particularly problems of drainage.

Different factors were already mentioned as possible reasons for the deviation in the individual cases: a porosity deviating from the average value and in certain – but not numerous – cases the presence of some air. Furthermore the assumption, held till now, that the clay always occurs between the sand particles in the same way, is certainly not quite true. A part of the clay in marine sandy deposits is present e.g. as pellets of excrements and the quantity can differ from one case to another. Such pellets contribute more to the building up of the porous skeleton than to the blockage of existing pores.

Finally it appears from a comparison of the conductivity results in vertical and horizontal directions that the so-called homogeneous soils are often more or less layered. As previously stated, the horizontal conductivity of a layered soil is higher than the conductivity of a homogeneous layer having the same average composition; the degree to which the 'homogeneous' soil is layered will accordingly influence the conductivity. Particularly in the case of clay layers in a sandy envelop the tendency will be for the actual conductivity to be higher than that estimated from the average composition.

This last consideration gives a warning in applying table 33, the table is explicitly applicable to marine soils which are more or less homogeneous. If alternating layers of varying coarseness or/and clay content are found in the soil, and mixed during the process of boring, it will not be possible to estimate the conductivity of the profile from the average composition. A second warning is that this table is not applicable to sandy soils having secondary pores which, if present in considerable quantities, disturb the relationship between conductivity and granular composition.

Hydraulic conductivity of marine soils in disturbed and dried condition, determined by the laboratory permeameter method

In table 34 the data of 20 soils, investigated in two ways, are recorded: A, results of undisturbed cores carried out by the field permeameter method; B, results of samples in dried and disturbed condition by the laboratory permeameter method.

TABLE 34. Hydraulic conductivity (m/d) of samples, investigated as undisturbed cores by the field permeameter method (A) and in dried and disturbed condition by the laboratory permeameter method (B.)

U figure class	% clay class							
	< 2		2–5		5–7½		> 7½	
	A	B	A	B	A	B	A	B
< 80	10.6	11.8						
	6.8	8.1						
80–120			0.4	3.8				
			1.4	1.8				
120–170	1.2	2.3	1.1	1.7	0.3	0.5	0.03	0.3
> 170	0.4	0.7	0.8	1.3	0.1	0.3	< 0.01	0.2
	0.14	0.5	0.3	0.6	0.04	0.35	0.01	0.08
			0.1	0.7	0.11	0.6	0.03	0.4
							< 0.01	0.15

It is obvious from this table, that the conductivity of practically all the samples is higher in disturbed condition. With the coarsest samples, which have also a lower clay content, the difference is small, but with the finer and more clayey ones, the conductivity of the disturbed samples is often 10 times higher than that of the natural soils. Especially with the more clayey soils, aggregates of sand and clay particles are formed when the sample is ground after drying; these aggregates are much bigger than the clay aggregates originally present in the natural soil. Consequently they do not block the pores, but contribute to the building up of the porous skeleton. Table 34 is a proof, that even for sandy marine soils the determination of the conductivity in dried and disturbed condition yields erroneous results.

SUMMARY

Hydraulic conductivity is an important property of the soil because, among other things, it determines the proper spacing of drains. It depends on the size and number of pores existing in the soil. In the deeper layers of marine sandy sediments which occur in one grain structure and do not contain big holes (e.g. cracks or channels made by roots or soil organisms) these pores arise simply because the sand particles do not fit together precisely. The coarser the sand particles the bigger the pores and hence a relationship exists between the particle size and conductivity.

Clay particles occur mainly as small porous aggregates in marine sandy soils, but the pores are so small that these aggregates can be considered to be impermeable. The clay aggregates are situated, to some extent at least, between the sand particles; thus they block the pores and reduce the conductivity. The extent to which these pores are blocked therefore depends, among other things, on the clay content. Thus it is reasonable to expect a relationship between the conductivity on the one hand and size of the sand particles and clay content on the other. It is important to come to a better understanding of this relationship because it is easier to determine the granular composition than conductivity and furthermore such data are often already available. Thus, once the relationship is known, conductivity could be deduced from the granular composition.

Several types of methods can be used in the measurement of conductivity and in this study determinations were carried out in four different ways:

1. on disturbed samples in the laboratory (fig. 4),
2. on undisturbed cores in the field (fig. 5),
3. by the auger hole method in the field (fig. 2) and
4. by the drain discharge method in the field (fig. 3).

Much attention has been paid to the manner of determining conductivity in disturbed samples and although the basic method is very simple, numerous difficulties have been encountered. A method has been developed in which it was possible to obtain values of conductivity which remained constant for a considerable time (table 8); at the same time this method allowed a measurement under conditions which corresponded as closely as possible to those in the field. In this method samples were freed from air and fully saturated with water before investigations commenced, and the measurements themselves were made using a disinfected dilute salt solution which was allowed to pass through the soil column from bottom to top under a low hydraulic head.

One of the chief obstacles in obtaining values which remained constant with time was the evolution of air from the flowing water which blocked the pores of the lowest part of the soil column. It seems highly probable that this - in any case in sandy soils – is really the major factor in the decrease of conductivity with time, often more important than the factors advanced by numerous other workers. In practice this problem was satisfactorily overcome by measuring only the conductivity of the upper part of the soil column.

The conductivity determinations which were made using undisturbed samples, were carried out with a simple field apparatus and without taking any of the above precautions. Nevertheless, it appeared from comparison with values obtained when these precautions were taken indeed, that the results could be regarded as being fairly reliable (table 13). This resulted from the fact that the soils investigated were sands, virtually air-free, practically at the maximum point of swelling and contained no large holes. A decrease in conductivity with time was again detected in this case, probably also due to the evolution of air; this difficulty was overcome by making the determinations as quickly as possible.

The auger hole method and the drain discharge method lend themselves less readily to methodical investigations, and assessements of their reliability can only be made by comparing the results with those obtained by other methods. It appeared that calculations of conductivity based on drain discharge measurements involve the making of several assumptions and the introduction of a number of corrections so that the reliability was lower than expected.

Particle diameter of the sand and conductivity are related to each other in a number of different formulas which can be converted to the same basis, the most suitable formula being chosen according to the results of investigation (p. 50). Within this formula, in which the conductivity depends on the sand particle diameter given as specific surface (U, see page 26) and the porosity, an empirical coefficient (μ) is involved, which has been determined by Hooghoudt for Dutch soils. As Hooghoudt did not determine this coefficient for sands of mixed composition but only for homogeneous subfractions, it was thought desirable to redetermine this coefficient for some soils of marine origin, but in fact the same value was obtained (p. 49). Both Hooghoudt and the author determined this coefficient for sands which had been freed from clay.

The influence which the clay exercises on the relation between particle size of sand and conductivity was firstly investigated in artificial mixtures. The influence of the clay content on conductivity depends on the type of clay and the form in which it occurs, for example montmorillonite decreases conductivity more strongly than illite. Coarse clay aggregates of illite have little influence on conductivity; they are too big to block the pores and thus they contribute to the building up of the porous soil skeleton.

The addition of fine clay aggregates causes a drop in conductivity which is much less marked in finer sands than in coarser sands. The curve indicating the relationship between conductivity and clay content has a definite concave form in the case of coarser sand but not in the case of the finer sand (fig. 15). Kneading the clay with sand has a very considerable influence in decreasing conductivity.

A possible method of elucidating the behaviour of fine clay aggregates in coarser and finer sand is to make microscope slides of different samples. It appeared that in the coarser sand, the bigger pores which occur in relatively small numbers but which are the most important for water movement, are firstly blocked, and that this blockage can take place even with small amounts of clay. With further additions of clay a general filling up of the pores takes place; moreover the clay aggregates contribute to the building up of the porous skeleton. Hence the effect of greater amounts of clay on conductivity is relatively much less. In finer sands, big pores are rare or absent; herein, the last process dominates from the beginning.

It appeared that there is a quantitative relationship between the number and size of pores which can be counted under the microscope on the one hand and conductivity on the other (fig. 8). The conductivity values calculated from these counts were, however, found to be much too high and this indicates that various assumptions made in the well known Kozeny/Carman formula (p. 20) cannot be regarded as totally correct.

Through these investigations it has been possible to shed more light on the effect of clay content on conductivity. At the same time it has been found that the clay aggregates have no specific influence on conductivity other than that of blocking the pores.

In the study of the relationship between granular composition and conductivity of natural soils it is of interest to note that a number of correlations exists between different properties of the soil. The granular composition of sand obeys a certain distribution pattern and consequently the U figure, the median and Hazen's effective size are closely linked (fig. 12). It is therefore clear why a parameter such as Hazen's effective size, which is in itself of little significance, can be useful in a conductivity formula.

In nature, the clay content and the sand fineness are correlated in the sense that coarser sand rarely has a high clay content. In finer sand, however, both low and high clay contents occur.

The importance of porosity lies in the fact that conductivity is positively correlated with porosity. Porosity itself increases in the soil with clay content on account of the fact that the clay aggregates themselves are porous, but this is in fact of no importance in connection with conductivity because the pores in the clay aggregates are much too small to influence water movement. Thus, conductivity depends only on the porosity of the sand, after the influence of the clay has been subtracted. This porosity appeared to be practically constant and thus in field investigations it is not necessary to take porosity into account.

Air is rarely encountered with, in appreciable amounts, in the deeper layers which play the most important role in drainage, and in the soils investigated it can be accepted that this factor had no effect on conductivity.

It appeared that there is a large difference between the conductivity of samples from which the clay had been removed and that of samples from natural subsoils with a low clay content, so that the previously determined coefficient μ should not be used in calculations for natural soils, although this in fact is the present practice in the Netherlands. It seems that this mistake has not been noticed largely because most of the samples which had a low clay content were studied in a dried condition, and that in this case the samples behave more or less as pure sands.

Even in the apparently fairly homogeneous marine sands, it frequently appeared that there was a difference between the conductivity in the vertical and horizontal direction, but as the horizontal conductivity is the most important in questions of water movement, no further reference will be made to vertical conductivity.

In the subsoil of natural marine sands with a low clay content, there is also a correlation between conductivity and U figure (fig. 13); this correlation being similar to, but at a lower level as that for clay-free sands. The influence of clay in reducing conductivity is of the same relative order for all U figures. Small amounts of clay appeared, comparatively speaking, to reduce conductivity considerably more than larger amounts (fig. 14). The reason is probably the same as in the case of additions of fine clay aggregates to coarse sand.

All the results as far mentioned in this summary were obtained with undisturbed samples. A comparison was possible with the results of other methods – viz. the auger hole method and the drain discharge method – at some points in the spectrum of clay content and U figure. This comparison which has not been so far carried out on a large scale appeared on the whole to show satisfactory agreement between the different methods (fig. 16 and 17).

The relationship between conductivity, clay content and U figure obtained from data collected with the help of all these three methods is shown in table 33.

Finally it must be pointed out that determinations of conductivity made on disturbed and dried samples give inaccurate results even in the case of sands containing relatively little clay (table 34).

SAMENVATTING

De doorlatendheid van de grond is een belangrijke eigenschap, o.a. omdat bij drainage de drainafstand in hoge mate afhangt van deze doorlatendheid. De doorlatendheid wordt bepaald door grootte en aantal van de poriën, die in de grond voorkomen. In de ondergrond van zandige mariene afzettingen, die in éénkorrelstructuur verkeren en waarin grotere holten (scheuren, gangen van plantaardige en dierlijke oorsprong) ontbreken, bestaan deze poriën uitsluitend uit de ruimten, die ontstaan doordat de zandkorrels niet geheel aan elkaar sluiten. Naarmate de zandkorrels grover zijn, zijn ook de tussengelegen ruimten groter en er bestaat dus een verband tussen de korrelgrootte van het zand en de doorlatendheid.

In mariene zandgronden komt de klei voornamelijk voor als kleine poreuze aggregaten; de poriën hierin zijn echter zo klein, dat deze aggregaten als ondoorlatend kunnen worden beschouwd. De kleiaggregaten liggen althans gedeeltelijk tussen de zandkorrels; zij blokkeren dus poriën en verlagen daardoor de doorlatendheid. De mate, waarin de poriën tussen de zandkorrels worden geblokkeerd, hangt o.a. af van het kleigehalte. Er moet dus een verband bestaan tussen doorlatendheid enerzijds en korrelgrootte van het zand en kleigehalte anderzijds. Kennis van dit verband is belangrijk, omdat gegevens over de granulaire samenstelling vaker beschikbaar zijn of gemakkelijker verkregen kunnen worden dan die over de doorlatendheid zelf. Bij kennis van dit verband kan uit de granulaire samenstelling de doorlatendheid van de grond worden afgeleid.

De doorlatendheid van de grond kan op verschillende manieren worden bepaald. In deze studie zijn de volgende methoden toegepast:

1. in het laboratorium in geroerde monsters (fig. 4);
2. te velde in ongeroerde monsters (fig. 5);
3. te velde met behulp van de boorgatmethode (fig. 2);
4. te velde met behulp van afvoermetingen van drainages (fig. 3).

Aan de methodiek van de bepaling van de doorlatendheid in geroerde monsters werd veel aandacht geschonken. De foutenbronnen bij deze, op zich zelf zeer eenvoudige bepalingswijze zijn nl. talrijk. Er werd een methode ontwikkeld, waarbij het mogelijk was om de doorlatendheid gedurende geruime tijd constant te houden (tabel 8) en de meting tevens te verrichten onder omstandigheden, die, voor zover mogelijk, aansluiten aan die te velde. De monsters werden daartoe vóór de eigenlijke bepaling ontlucht en verzadigd met water, er werd gewerkt met een kleine hydraulische gradient en de percolatie geschiedde van beneden naar boven, terwijl voor deze percolatie zwak zouthoudend gedesinfecteerd water werd gebruikt.

Eén van de grote moeilijkheden voor het verkrijgen van waarden, die geruime tijd constant blijven, bleek de lucht te zijn, die zich uit het percolerende water in het onderste deel van de permeameters afscheidt en die de poriën in het onderste deel van de grondkolom blokkeert. Deze luchtafscheiding is vermoedelijk meer dan iets anders verantwoordelijk voor het teruglopen van de doorlatendheid in verloop van tijd, die talrijke onderzoekers hebben geconstateerd en aan andere factoren geweten.

Voor dit probleem van de luchtafscheiding werd een bevredigende oplossing gevonden, en wel door de doorlatendheid alleen in het bovenste deel van de grondkolom te meten.

De bepaling van de doorlatendheid in ongeroerde monsters geschiedde met een eenvoudig veldapparaat, waarbij geen van de hierboven genoemde voorzorgen waren genomen. Door de hiermede verkregen resultaten te vergelijken met uitkomsten, waarbij deze voorzorgsmaatregelen wel waren genomen, bleek dat bij de onderzochte gronden ook deze resultaten betrouwbaar geacht kunnen worden (tabel 13). Dit was mede te danken aan het feit, dat de onderzochte gronden zandig waren, in vrijwel maximale zwellingstoestand verkeerden, luchtvrij waren en geen grotere holten bevatten. Ook bij deze bepalingsmethodiek trad op de duur een daling van de doorlatendheid op, vermoedelijk eveneens door afscheiding van lucht; het bezwaar hiervan werd voorkomen, door de meting zo vlug mogelijk na het aanzetten te verrichten.

Boorgatmethode en drainafvoermethode lenen zich minder voor methodisch onderzoek; pas uit de onderlinge vergelijking van de resultaten der verschillende methoden kan hun al dan niet betrouwbaarheid blijken. Wel maakte een bespreking van de drainafvoermethode het duidelijk, dat voor de berekening van de doorlatendheid uit grondwaterstand en afvoer veel veronderstellingen moeten worden gedaan en veel correcties aangebracht, hetgeen de betrouwbaarheid der verkregen uitkomsten niet verhoogt.

Formules, die het verband aangeven tussen de korrelgrootte van het zand en de doorlatendheid, zijn er vele. Al deze formules kunnen echter tot enkele typen worden teruggebracht, waarvan aan de hand van enkele onderzoekingen de meest waarschijnlijke werd uitgekozen (blz. 50). In deze formule, waarin de doorlatendheid afhangt van de korrelgrootte van het zand, uitgedrukt als specifiek oppervlak (U, zie blz. 26 en van de porositeit, komt een empirisch vast te stellen coëfficient (μ) voor, die voor Nederlandse gronden al door HOOGHOUDT is bepaald. Daar HOOGHOUDT deze coëfficient bepaald had in homogene subfracties, en niet in zanden van gemengde samenstelling, werd het gewenst geacht de grootte van deze coëfficient voor de betrokken gronden opnieuw te bepalen. Er werd echter ongeveer dezelfde waarde gevonden (blz. 49). Het is van belang op te merken, dat zowel HOOGHOUDT als de schrijver deze coëfficient bepaalden in kleiloos gemaakte zanden.

De invloed, die klei uitoefent op het in bovengenoemde formule aangegeven verband, werd in eerste instantie onderzocht in kunstmatige mengsels van klei en zand. De invloed van het kleigehalte op de doorlatendheid bleek af te hangen van de aard van de klei en van de vorm, waarin deze voorkomt. Montmorilloniet verlaagt de doorlatendheid veel sterker dan illiet. Grove kleiaggregaten van illiet – op welke kleisoort alle verdere proeven betrekking hadden – hebben op de doorlatendheid nauwelijks invloed; zij zijn te groot om de poriën te blokkeren, en doen daardoor mee aan de opbouw van het poreuze bodemskelet. Fijne kleiaggregaten verlaagden de doorlatendheid van fijner zand veel minder dan van grover zand; bij grover zand was de curve, die het verband tussen doorlatendheid en kleigehalte aangeeft, uitgesproken concaaf, bij fijner zand niet (fig. 15). Wanneer de klei door het zand wordt gekneed, heeft zij de grootste invloed op de doorlatendheid.

Het bleek mogelijk het verschillend gedrag van fijne kleiaggregaten in grover en in fijner zand te verklaren met behulp van de van monsters gemaakte slijpplaatjes. Bij het grovere zand worden in de eerste plaats de grotere poriën, die betrekkelijk gering in aantal zijn, doch voor de waterbeweging zeer belangrijk, opgevuld; voor deze opvulling is maar weinig klei nodig. Bij toenemend kleigehalte vindt een algemene opvulling van de resterende poriën plaats, terwijl de kleiaggregaten daarnevens meewerken aan de opbouw van het poreuze bodemskelet en dan de doorlatendheid minder verlagen. Bij het fijnere zand, waar grove poriën veel minder voorkomen, is dit proces reeds bij een geringe kleitoevoeging overheersend.

Er bleek een quantitatief verband te bestaan tussen het door de microscoop waargenomen poriënbeeld en de doorlatendheid (fig. 8). Berekening van de doorlatendheid uit dit microscopische poriënbeeld leverde echter te hoge waarden; dit is een bewijs, dat verschillende aannamen in de bekende formule van KOZENY-CARMAN (blz 20) voor de berekening van de doorlatendheid uit de korrelgrootte onjuist moeten zijn.

Door deze proeven werd het inzicht in de betekenis van het kleigehalte voor de doorlatendheid verhoogd; tevens werd gevonden, dat de kleiaggregaten geen specifieke invloed op de doorlatendheid hebben, doch alleen doordat zij poriën blokkeren.

Wanneer men het verband tussen granulaire samenstelling en doorlatendheid bij natuurlijke gronden nagaat, heeft men in de eerste plaats te maken met het feit dat er een aantal correlaties tussen de verschillende eigenschappen van de grond bestaat. Zo vertoont de granulaire samenstelling van het zand een grote wetmatigheid; als gevolg daarvan hangen U-cijfer, mediaan en effective size volgens Hazen nauw samen (fig. 12) en het is daardoor duidelijk, waarom een op zich zelf weinig zinvolle parameter als Hazen's effective size bruikbaar kan zijn voor een doorlatendheidsformule.

Kleigehalte en zandgrofheid zijn in die zin gecorreleerd, dat bij grove zanden geen hoog kleigehalte voorkomt; bij fijn zand is zowel een hoog als een laag kleigehalte mogelijk.

De porositeit is voor de doorlatendheid van belang, omdat de doorlatendheid positief gecorreleerd is met de porositeit. In de grond neemt de porositeit toe met het kleigehalte, omdat de kleiaggregaten in de grond zelf poreus zijn. Deze toename van de porositeit bij hoger kleigehalte is voor de doorlatendheid echter van geen belang, omdat de poriën in de kleiaggregaten veel te klein zijn om invloed te hebben op de waterbeweging. Men heeft voor de waterbeweging uitsluitend te maken met het poriëngehalte van het kleiloos gedachte zand. Dit bleek nagenoeg constant te zijn; de porositeit is dus geen factor, waarmee men bij het onderzoek te velde rekening behoeft te houden.

Lucht bleek in de diepere lagen, die voor de waterbeweging bij drainage de belangrijkste zijn, niet voor te komen; bij de onderzochte gronden speelt deze, de doorlatendheid verlagende, factor dus geen rol.

Er bleek een groot verschil te bestaan tussen de doorlatendheid van kleiloos gemaakte monsters en die van natuurlijke gronden uit de ondergrond met een laag kleigehalte. De hiervóór bepaalde coëfficient μ voor de berekening van de doorlatendheid geldt dus niet voor natuurlijke gronden, hoewel deze daarvoor in Nederland algemeen wordt gebruikt. Dat op deze fout tot nu toe nooit de aandacht is gevallen bleek te berusten op het feit, dat de meeste kleiarme monsters onderzocht worden in gedroogde toestand; gedroogde kleiarme grond gedraagt zich in dit opzicht min of meer als zuiver zand.

Zelfs in de toch op het eerste gezicht tamelijk homogene mariene zanden bleek herhaaldelijk verschil te bestaan tussen de doorlatendheid in verticale en in horizontale richting. Daar voor de waterbeweging de horizontale doorlatendheid de belangrijkste is, hebben de hierna volgende beschouwingen daarop betrekking.

Ook bij natuurlijke kleiarme mariene zanden uit de ondergrond bestaat er een verband tussen doorlatendheid en U-cijfer (fig. 13). Dit verband vertoont verwantschap met dat van kleiloze zanden, doch ligt lager. Met het toenemen van het kleigehalte neemt de doorlatendheid af; de relatieve invloed van het kleigehalte op de doorlatendheid is bij alle U-cijfers ongeveer van dezelfde orde. Kleine hoeveelheden klei bleken de doorlatendheid verhoudingsgewijs sterker te verlagen dan grote (fig. 14); hiervoor moet wel dezelfde verklaring gelden als voor de invloed, die toegevoegde fijne kleiaggregaten op grover zand hebben.

Alle tot nu toe besproken resultaten werden verkregen bij het onderzoek van ongeroerde monsters. Op bepaalde plaatsen van het spectrum van kleigehalte en U-cijfer konden deze resultaten vergeleken worden met die van de boorgat- en de drainafvoermethode; een vergelijking, die tot nu toe niet op grote schaal was uitgevoerd. De overeenstemming tussen de verschillende methoden bleek in 't algemeen bevredigend (fig. 16 en 17).

Met behulp van het met deze drie methoden verzamelde cijfermateriaal werd een tabel ontworpen, die het verband tussen doorlatendheid, kleigehalte en U-cijfer aangeeft (tabel 33).

Ten slotte werd aangetoond, dat zelfs voor tamelijk kleiarme zanden bepaling van de doorlatendheid in geroerde, gedroogde monsters onjuiste resultaten geeft.

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