of interest mainly in order to show the difference in comparison with cohesive soils.

Considering the lines for the sand-loam mixtures (Fig. 3) it is noticed that the good soil mortars showing but small differences from each other differ noticeably from the bad ones respectively from the sands. Mixture Nr 7 for instance being bad on account of a too large percentage of clay has far higher values of moisture content. On the other side there is a striking difference between the mixtures Nr. 10 and 11 with regard to the maximum of their shearing strength which for mixture 11 amounts to about 1/5 only of that for Nr. 10. Therefore Nr. 11 can easily be classified as sand, mixture 10 on the other hand must be marked as soil mortar. It is possible, however, that the maximum of shearing strength being dependent not only on the percentage of clay but also on other matters would show different results if samples would be tested taken directly from the surface of a road instead of soil mixtures made in the laboratory.

CONCLUSIONS.

By determination of the shearing strength as well as the moisture content it is possible to distinguish the soils numerically. The accuracy depends mainly on the moisture content. As an example two semi logarithmic diagrams are given showing both soil characteristics and explaining the behaviour of certain sand-loam mixtures.

If only the shearing strength is given,it describes the consistency of a certain soil better than the moisture content would do this.

The apparatus in its present form is not perfect but will be improved.

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SUB-SECTION II f

ELECTRO-OSMOSIS

II f 2 RESULTS OF LABORATORY INVESTIGATIONS ON THE ELECTRICAL TREATMENT OF SOILS

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INTRODUCTION.

The electrical treatment of soils has created the interest of the soil mechanics experts, especially in the years after the war. Since the first experiments by L. Casagrande a number of technical applications have been made, which proved the necessity of a closer study of this method of treatment, its possibilities and its limitations.

The opening phase of this study, as made by the authors in the Delft Laboratory, has resulted in some preliminary investigations, which will be described in the following pages.

Two phenomena resulting from the electrical treatment of soils were taken as a starting point for the authors' investigations.

a) the improvement of the mechanical properties of soils, resulting from an accelerated process of consolidation, including the so-called "electro-chemical hardening".

b) the possibility of influencing pore-water flow, and of establishing favourable hydraulic gradients in soil masses, which do not permit the application of the usual drainage methods (well pumping a.o.) because of their low permeability. This explains the use of the term "electrical drainage".

In order to investigate the effects of electrical treatment, with respect to the above-mentioned points, it was necessary to develop a suitable technique for laboratory experiments and to test a range of soils from coarse sand to fat clay.

FUNDAMENTAL THEORIES.

The changes in the soil brought about by an electrical treatment are the result of combined electrolytic and electrokinetic phenomena, varying strongly with the composition and the properties of both the soil (including the soil solution) and the electrodes used.

The effect of an electrical current primarily causes a transport of pore-water in the soil. This flow of porewater may be accompanied by a decrease of the water content (consolidation effect).

Secondly a hardening may occur as a consequence of electrochemical changes, like a precipitation of aluminum-hydroxyde (when a aluminum is used for the electrodes) and eventually a flocculation of colloidal clay substance (electro-chemical hardening of clays).

Both last-mentioned phenomena are usually not or partly reversible, causing an important decrease of compressibility and a subsequent increase of internal frictional resistance.

The transport of pore-water is usually referred to as an electrokinetic effect (electro-osmosis), which is made possible by an electrical charge of the soil particles due to the adsorption of ions from the soil solution. As the positive ions generally have a greater energy of hydration than the negative ions, the colloidal soil particles usually are loaded with a negative charge. Thus the water having a positive charge, will move towards the negative electrode.

In soils with a considerable salt content this effect is strongly diminished. The remaining transport of water will be mainly due to different hydration of the moving positive and negative ions in the soil solution (electrolytic transport of water).

Decrease of the water content, resulting from electrolytic decomposition of pore-water at the electrodes seems to be a factor of small importance in electrical drainage.

The amount of electro-chemical hardening of soils is strongly dependent on the material of the electrodes used. The formation of precipitates is strongest, when using electrodes consisting of amphoteric metals like aluminum and iron, while inert materials like carbon or platinum (and copper to some extent) are without a marked influence.

LABORATORY INVESTIGATIONS.

In order to find out if the mechanical properties of a soil are improved by electrical treatment, use has been made of the Delft tri-axial apparatus, the so-called cell-apparatus (fig. 1) as it was designed and called by Buisman 1).

This apparatus is used for routine-investigations on cylindrical samples either in disturbed or undisturbed state, It can be used as a consolidometer, with the additional advantage of measuring the lateral pressure during the process of consolidation, without influencing the vertical load increment. The pressure is measured in the fluid mantle, which acts as a rigid lateral support for the sample. The sample is surrounded by a rubber envelope, fixed to the top- and the bottom metal rings of the annular fluid container. The top of the rubber envelope is provided with a turned-down end fixed to the top metal ring. This improvement of the older type of apparatus allows the loading plunger to move freely downward over a distance of several centimeters, thus realizing a state of zero-side-friction. Lateral deformations are very slight as they are limited to the volume changes of the rigid part of the container, the supporting fluid and the rubber envelope, which will result from changes of lateral pressure.

Besides, the cell-apparatus is used for tri-axial purposes. Usually a vertical load-increment is kept constant either for a short time (quick test) or for a period of sufficient length, to attain a certain amount of consolidation (slow test). After that the lateral pressure is decreased, by letting out drops of water from the container, until the critical ratio of principal stresses is attained. This point in the test is marked by a constant (minimum) value of the lateral pressure. From a range of load-increments and the belonging critical states of equilibrium, Mohr's principal stress-circles can be computed. Results are then obtained as shown in fig. 5.

RESULTS OF TESTS WITH THE CELL-APPARATUS.

The material for these tests was taken from an undisturbed sample of heavy clay, with traces of peat. The sample, with a length of 45 cm and a diameter of 7 cm, was cut into three equal parts with a length of 15 cm. All three samples were placed in three identical cell-apparatus at the same time.

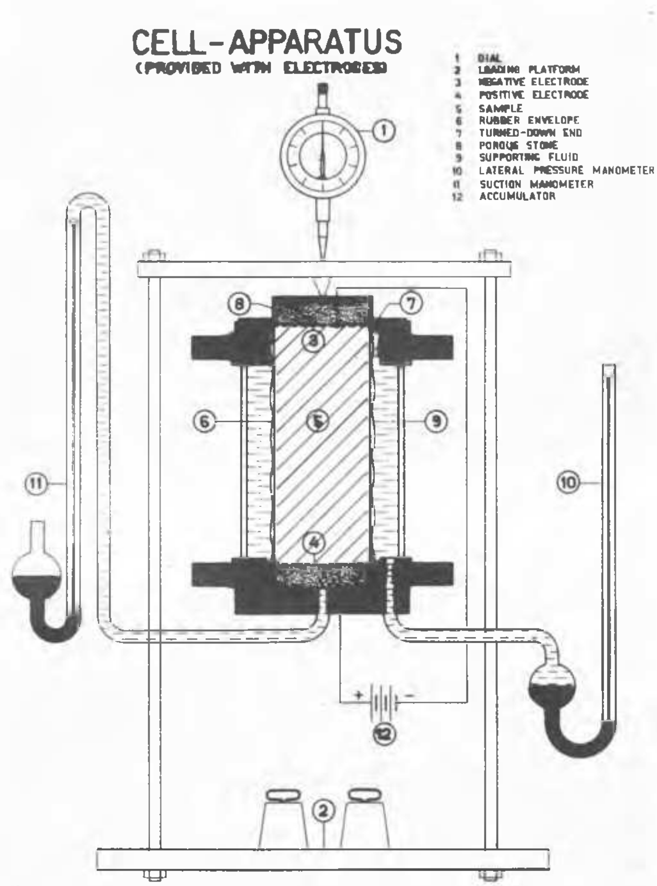

FIG. 1

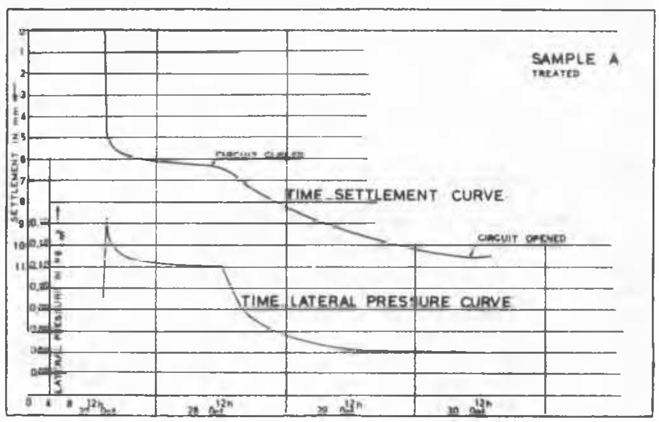

FIG. 2

For the sake of electrical treatment the apparatus were provided with aluminum electrodes (perforated circular plates between the ends of the sample and the porous stone.). The porous stone at the bottom of the sample was connected with a suction-manometer.

All tests started simultaneously with the application of a vertical load of 10 kg on the top of the samples. From this vertical stress-increment of 0.26 kg/cm² resulted lateral pressures of 0,165-0,148-0,149 kg/cm² of the samples a, b and c respectively (see diagrams of fig. 2 for sample a, fig. 3 for sample b, fig. 4 for sample c).

After 20 hours the lateral pressures had decreased to 0,122, 0,124 and 0,100 kg/cm² respectively, because of consolidation effects

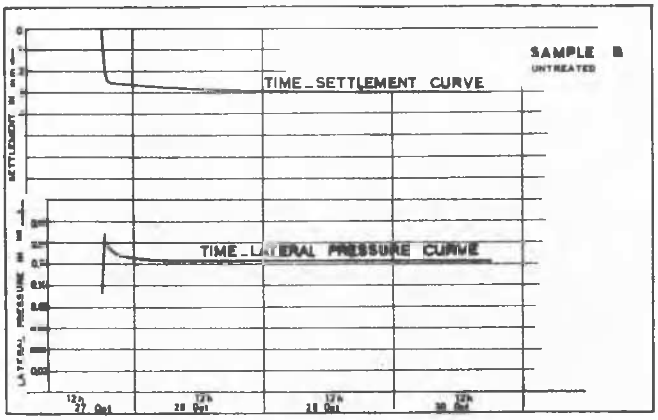

FIG.3

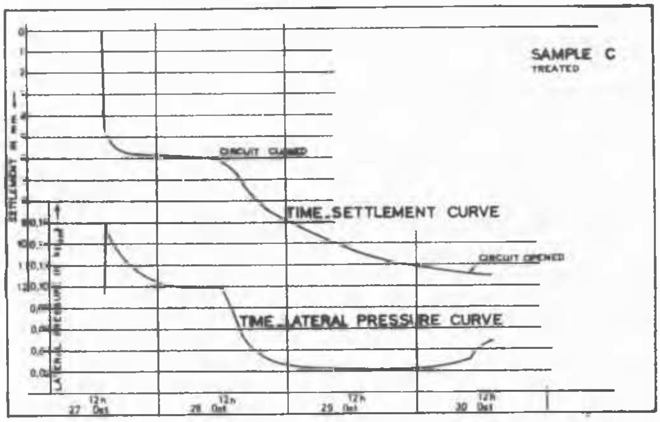

FIG.4

following the application of the vertical stress amounting to 0,26 kg/cm^2. So the ratios of principal stresses after a waiting period of 20 hours amounted to $\frac{0,122}{0,26} = 0,47$, $\frac{0,124}{0,26} = 0,48$ and $\frac{0,10}{0,26} = 0,38$ respectively.

The settlement speed had decreased considerably as can be seen from the top diagrams. Both aluminum electrodes of the samples a and c were then connected with the electrodes of an accumulator of 11,5 Volts, the top plate with the negative, the bottom plate with the positive electrode, thus causing a potential gradient of $\frac{11,5}{15} = 0,77$ Volt/cm in vertical direction over the height of the samples. Nearly immediately after closing the circuit, the samples a and c started to consolidate at accelerating speeds for a period of about 12 hours and then at slowly decreasing speeds over another 60 hours, after which the circuit was disconnected. During the 72 hours of electrical treatment the lateral pressures decreased in a similar manner, as can be seen from the bottom diagrams of figs. 2 and 4. A constant minimum value was attained after some 30 hours. The decreases amounted to, for sample a from 0,122 to 0,042 kg/cm^2 and for sample c from 0,100 to 0,022 kg/cm^2, thereby decreasing the principal stress ratios from 0,47 to 0,16 and 0,38 to 0,0845 respectively. Apparently an extremely favourable equilibrum state of stress resulted from the electrical treatment, as can be seen by comparing the final states of stress of the treated samples a and c with the same of sample b, which had been allowed an equal period of consolidation under the same vertical stress.

After breaking the circuit the samples a and c were allowed to remain under the same conditions as sample b for 4 hours. Apparently some swelling in both directions took place during that time, thereby increasing the lateral pressures.

RESULTS OF A SERIES OF CRITICAL STRESS COMBINATIONS.

Shortly after finishing the above-mentioned tests all three samples were subjected to a quick succession of critical stress combinations. The results, as plotted in Mohr's diagrams (fig. 5), show straight (or nearly straight) envelopes of the stress circles up to vertical stresses as high as 1,82 kg/cm^2. The equations of this straight lines can be computed from the diagrams as to be:

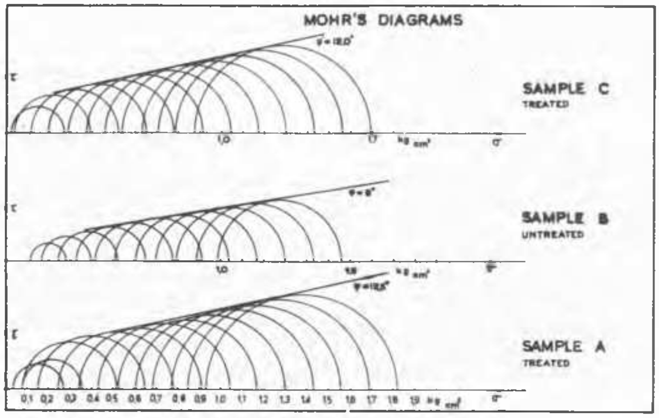

FIG.5

Sample	Equation	Apparent angle of internal friction φ'
a	$S' = 0,175 + 0,21\sigma$	12,5°
b	$S' = 0,095 + 0,155\sigma$	9,0°
c	$S' = 0,14 + 0,22\sigma$	12,0°

The difference of the frictional properties of the treated samples a and c on one part and the untreated sample b on the other part is thus clear. Both the cohesion and the (apparent) angle of internal friction are raised by the electrical treatment of the clay samples.

During the test the samples were kept immersed in water. The suction-manometers were installed for a two-fold purpose. It was assumed, that the rubber envelope would adhere sufficiently to the circumference of the sample to prevent a connection of the water contained in both porous stones. This seemed however not to be the case, as the suction-manometer failed to indicate any decrease of pore-pressure, which - according to the results to be discussed next - should follow up the application of an upwards directed electrical current. The only explanation seems to be the formation of fine creases, which are often observed in the rubber envelope, because of lateral consolidation of the sample. Along these creases a communication with the water on top of the sample might be possible.

The compression of the samples a and c in the vertical directions after 72 hours of treatment were 22 and 28 times those of untreated sample b after the same period. The compression amounted to 2,7%, 0,125% and 3,45% of the height of the samples.

RESULTS OF THE TESTS WITH THE ELECTROSMOMETER.

The principle of the electrosmometer was adopted from a paper by Haefeli and Schaad 2). In this paper results are discussed, obtained with an electrosmometer with vertical axis. This apparatus had a disadvantage, which lead Haefeli and Schaad to propose a scheme of electrosmometer with horizontal axis (l.c.p.).

The apparatus of the Delft Research Department was constructed according to this scheme. The diagram in fig. 6 shows the vertical section along the horizontal axis of this apparatus.

The sample with a diameter of 6,5 cm and a thickness of 2,5 - 3 cm is enclosed between two perforated Cu-electrodes. The negative electrode is held in a fixed position, the positive electrode is used as a loading disc. The loading device consists of a plunger with a cantilever and a loading platform.

Under the action of the potential gradient, porewater will flow from the positive to the negative electrode. At the positive side of the sample water is kept at a constant level in the filling tube. The pore-water flowing out at the negative side of the sample gradually fills the piezometric tube, until an equilibrium between electrical and hydraulic gradient is established. In this same tube H-gas bubbles, which develop as a result of electrolytic decomposition of the pore-water at the negative electrode, may ascend freely.

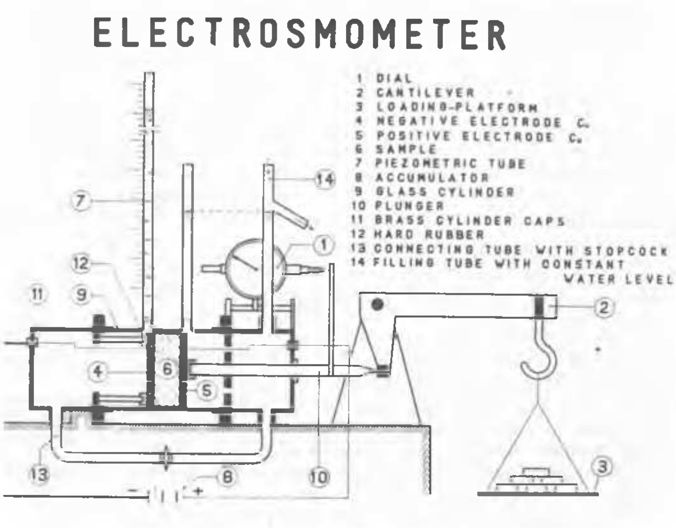

FIG.6

THEORETICAL CONSIDERATIONS.

Schaad and Haefeli used the similarity between electrical and hydraulic gradient to express the flow of pore-water in electrical magnitudes.

According to the law of Darcy, the velocity of pore-water flow is expressed by:

$$v_o = k.i$$

where:

v_o = velocity of flow in cm/sec, relative to the cross-section of the sample.
k = coefficent of permeability in cm/sec
i = hydraulic gradient.

The velocity of pore-water flow resulting from an electrical potential gradient E, according to Haefeli and Schaad can be expressed by:

$$v_E = k_E.E$$

where:

v_E = velocity of flow in cm/sec
k_E = coefficient of electrical permeability in $\frac{cm^2}{Volt.\ sec}$
E = electrical potential gradient = $\frac{U}{d}$ Volt/cm
U = electrical tension between electrodes in Volts
d = distance between electrodes = thickness of sample.

The total velocity of pore-water resulting from an electrical and a hydraulic gradient acting at the same time is:

$$v_{tot} = v_o + v_E = k.i + k_E.E$$

PIEZOMETRIC RISE IN THE TUBE.

The height of the piezometric rise in the tube can be computed on the strength of the above mentioned formulae.
With:

F = cross-section of the piezometric tube
O = " " " sample
h = height of rise above the constant level at time t after the start of the test, and where k, k_E, U and d having the meaning indicated above, the equation gives the magnitude of k_E.

This equation may be derived as follows:
During a small lapse of time dt, the piezometric rise be dh. The small amount of flow through the sample during the time-element dt thus becomes dh.F.

The electrical gradient causes a flow amounting to:

$$dQ_E = k_E.E.O.dt$$
$$= k_E.\frac{U}{d}.O.dt$$

The hydraulic gradient causes a flow in the opposite direction, amounting to:

$$dQ_h = k.i.O.dt$$
$$= k.\frac{h}{d}.O.dt$$

The flow-equations then becomes:

$$dh.F = Q_E - Q_h$$

and the differential equation:

$$\frac{dh}{dt} = \frac{(k_E.U - k.h).O}{F.d} \qquad (1)$$

or:

$$\frac{dh}{(k_E.U - k.h)} = \frac{O}{F.d}dt$$

The solution of this equation gives the magnitude of k_E, as:

$$k_E = \frac{k.h}{U}\cdot\frac{e^{\frac{k.O.t}{F.d}}}{\left(e^{\frac{k.O.t}{F.d}} - 1\right)} \qquad (2)$$

and:

$$h = \frac{k_E}{k}.U.\frac{\left(e^{\frac{k.O.t}{F.d}} - 1\right)}{e^{\frac{k.O.t}{F.d}}} \qquad (3)$$

The maximum height of rise h_{max} may be obtained from the condition $\frac{dh}{dt} = 0$, in equation

(1):

$$k_E . U - kh_{max} = 0$$

thus:

$$h_{max} = \frac{k_E}{k} U \qquad (4)$$

This condition is satisfied at $t = \infty$

RESULTS OF ELECTROSMOMETER-TESTS.

The permeability coefficient k was determined in the electrosmometer, according to the "falling head" method, before and after the electric treatment. The results for the same peaty clay soil, as used for the investigations with the cell-test, were: 30.10^{-6}cm/sec before and 5.10^{-6} cm/sec after the treatment. This effect was observed with all the tested soils. Fig. 7 shows the result of the piezometric rise obtained with an electrical treatment. The electrical tension between the electrodes U was 5,7 Volts during the test. The thickness of the sample d amounted to 3,0 cm, so the electrical gradient E= 1,9 Volt/cm. The piezometric rise is plotted against time and shows a gradual rise to 127 cm, 29 hours after the start of the test. Afterwards the piezometric head fell to 54 cm at 100 hours after the start of the test.

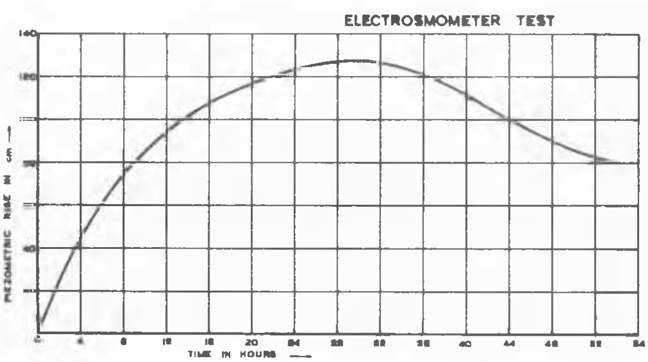

FIG.7

This result is contrary to the theoretical equation (3), which was derived on the assumption of constant values of k_E and k. According to this equation maximum rise should be obtained at $t = \infty$ and be equal to $\frac{k_E}{k}$.U. The gradual decrease of height after reaching its maximum, shows that the ratio $\frac{k_E}{k}$ decreases with time, as U remains constant throughout the test. The decrease of the hydraulic permeability as stated above, indicates a still more substantial decrease of k_E than would be concluded on the strength of the results of fig. 7.

Before starting the electrical treatment, the sample was loaded with 0,12 kg/cm^2. The settlement during the treatment amounted to 0,35% of the thickness of the sample.

PROBABLE CAUSES OF THE DECREASE OF THE ELECTRICAL PERMEABILITY.

The source of this decrease is mainly due to colloid-chemical and electrochemical phenomena. Probably the following two effects were the most important ones:

Firstly the anode cupric-ions, which went into the solution had a strong flocculating power on the negatively charged colloidal soil particles (rule of Schulze and Hardy)

Secondly the cupric (positive) ions may cause the formation of insoluble copper compounds, depending on the composition and the acidity of the soil solution.

The decrease of hydraulic permeability is probably indirectly due to the above-mentioned phenomena.

CONCLUSIONS.

The results of the electric treatment of soils are studied in the cell-test and in the electrosmometer-test. The first-mentioned test shows to be especially suited for the study of the effects of electrical treatment on consolidation and internal friction properties of soils.

The electrosmometer-test is very suitable for measurements of the electrical and the hydraulic permeability.

Results of tests on "sandy" soils showed that all the properties mentioned above, were slightly or not influenced by the electrical treatment.

The opposite was encountered with all "clay" soils. One result should be mentioned in particular. The permeability coefficients as defined by Haefeli and Schaad showed a considerable decrease during a test of some days, especially with clay soils.

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