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APPLICATION OF ELECTRO-OSMOSIS TO THE EXECUTION OF CERTAIN WORKS ON WATER-BEARING SOILS

by

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(A translation)

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As early as 1936 tests were made in Germany with a view to applying the phenomena of electro-osmosis to the stabilization of slopes of excavations or trenches cut in very fine-grained (below 1/50mm) water-bearing soils, the drainage of which is nearly impossible by the classical methods. The method consists in the acceleration of the filtration by adding to the action of the "natural" hydraulic load, that of the "electro-osmotic load or pressure" obtained by a direct current which is made to flow through the soil to be drained. This method has been successfully applied since 1939 in the construction of important works which have been described among others in a report of the Department of Scientific and Industrial Research entitled: "The application of electro-osmosis to practical problems in foundations and earthworks" (Technical Paper no. 30, London, 1947).

Systematic laboratory tests were made recently by the Soil Mechanics Laboratory of "Ecole Polytechnique" of Zurich. A first report on these works was published under the signature of MM. W. Schaad and R. Haefeli in the "Schweizerische Bauzeitung", no. 16, 17 and 18, April-May 1947.

In the light of these publications, the author deemed that it would be of interest to summarize the present state of the process, which might find several applications in France.

I Mechanism of the phenomena of electro-osmosis and electrophoresis

a) General phenomena

1) If an aqueous solution is divided into two parts by means of a porous diaphragm and a difference of potential is established between these two parts, it will generally be noted that the liquid starts filtering through the diaphragm. This movement of liquid through the porous material under the influence of an electric field constitutes electro-osmosis. It was described for the first time in 1808, by Reuss.

2) If an electric field is established between two points of a liquid containing colloidal or noncolloidal particles in suspension, as for instance by immersing in the liquid two electrodes connected to the terminals of an electric generator, it is seen that the particles start moving either in the direction of the field by going toward the cathode, or in the opposite direction by going toward the anode. This phenomenon, which is general and occurs in turpentine as well as in water, with gas bubbles as also with solid dusts or emulsified liquid droplets 1/ is called electrophoresis.

3) The influence of a difference of pressures between two liquid masses separated by a membrane, which causes a filtration of the liquid through the membrane, brings about the occurrence of a difference of potential between the two parts of the liquid.2/ Likewise, if in the absence of a field small particles fall in a liquid, a difference of potential may take place between the upper layers and the lower layers of the liquid.

b) Theories

1) Hypothesis of the electric double layer

The phenomena of electrophoresis and electro-osmosis are interpreted from the hypothesis of the "double layer" formulated for the first time, in 1861, by Quincke. It consists in agreeing that a spontaneous electrification exists at the contact surface of a solid and a liquid previous to any exterior electric action. The surface of the solid becomes charged with a certain electric layer, an electric layer of opposite sign appearing in the liquid; the solid-liquid contact surface acts somewhat as the dielectric of a classical condenser.

1/ The electrical removal of dust from gas and smoke (Cottrel process) may be considered as a particular application of electrophoresis.

2/ One may connect to the same phenomenon the electrification of liquid hydrocarbons flowing in pipes on which considerable charges also appear, if their electric insulation is sufficient; large sparkles may result which might cause the explosion or fire of the hydrocarbons. Therefore a special regulation controls the careful grounding of such pipes and tanks.

In the case of electrophoresis the transfer of the particles in suspension is due to the action of the electric field created by the flow of the current, on the electric charges carried by these particles. If, for instance, the particle is negatively charged relative to the liquid, it will stem the current to settle on the anode (+); if it is positively charged it will migrate in the opposite direction. In electro-osmosis the electric charge of a particle of the liquid moves through the same mechanism in the direction of the lines of force and carries along the said particle and also, through friction, the adjoining particles.

Thus, the mechanism of electro-osmosis and electrophoresis (which both imply the same relative displacement of the liquid with regard to the solid) is linked with the mechanism of electrolysis according to Arrhenius theory; but whereas in the latter case the ion sign, and consequently the direction of its displacement, is well determined by its chemical function (the metallic ions are positively charged and migrate toward the negative pole; the metalloid ions are negatively charged and migrate toward the positive pole), in the electric osmosis the charge of the particle is not known a priori.

In 1898 Cohen thought he had found a simple rule which would enable the previous indication of the particle sign before any exterior electric action. According to this rule a body of high dielectric constant becomes positively charged at the contact of a body of lower dielectric constant. Thus, relative to water, which has a particularly high electrical constant (approximately 80 to 1.4 for air), the rule of Cohen indicates that most bodies should become negatively charged. This rule, generally applicable to pure liquids, does not apply as well to electrolysis solutions.

In 1905 J. Perrin showed that whereas the electrification of the particles and of the liquid is actually due to the ions coming from the dissociation of the traces of salt always present in the liquid, this electrification may change sign according to the nature and the quantity of matters in solution. According to this author, the direction of the transfer depends upon the acid or alkaline reaction of the liquid in which the particles are present, that is upon its pH.

Besides, in some cases the change of direction of the transfer corresponds to an extremely small variation of the reaction of the medium. Moreover, it is possible to reverse the direction of the migration of the particles by adding to the alkaline or acid liquid a metallic salt which originates anions or polyvalent cations (potassium ferricyanide, chloride of lanthanum, etc.). Actually no general law seems to summarize all the observations, and it is probable that the special chemical affinities of the substances present play a great part.

Hereafter, consideration will be given to the hypotheses which were put forward to explain the origin of the electric double layer which sets up at the contact of a solid and a liquid pervious to any exterior electric action.

In regard to the applications, the most suggestive hypothesis consists in linking this electrification to the adsorption by the solid walls of the ions of a certain sign existing in the liquid (due to the dissociation of the traces of salt existing in the latter), the ions of the other sign remaining in the liquid and close to the said walls due to the attraction that two charges of contrary sign exert on each other. Thus it is simple to explain the influence of very small quantities of acid or of base on the course of electrophoresis and that of electro-osmosis (opposite to the first); particles of very diverse nature (coal, silica, sulphur, gelatin, silk, etc.) become positively charged in water with an admixture of extremely small quantities of any monovalent acid, and will be negatively charged in water with very small quantities of any monovalent base.

2) Helmholtz - Perrin theory

a) Electrophoresis - Helmholtz and later Perrin went further into the qualitative concepts of Quincke and established a theory in quantitative agreement with the phenomena that were observed particularly on capillary tubes. The essential of the theory developed by Mr. Perrin follows:

Let us consider a capillary tube which puts into communication two liquid masses maintained at the same level so that no hydrostatic pressure occurs. An electric field parallel to the tube is brought into action and a state of flow being attained u represents the mean velocity of the liquid in the tube. Assuming that one of the electric layers is adherent to the wall whereas the other layer acts as a very thin layer of equal charge and opposite sign at a distance d from the capillary wall and moves at the velocity u of the liquid which it carries away.

H is the electric field and σ the electric density of the layer; the electric charge per unit of area of this layer is σH.

Now, by the very definition of the coefficient of viscosity η of the liquid, this electric charge is equal to the product of the coefficient of viscosity times the velocity gradient, or by assuming as first approximation that the flow occurs all at once, that is that the velocity of the fluid passes from u to 0 in the thickness d of the double layer:

$$\sigma H \rho = \eta \frac{u}{d}$$

which may be written when introducing the electric moment d of the double layer:

$$\sigma d = \eta \frac{u}{H} \qquad (1)$$

If ϕ indicates the flow of the capillary tube, then

$$\phi = \pi r^2 u \text{ or } u = \frac{\phi}{\pi r^2}$$

Combining this value of u with (1), we obtain

$$\sigma d = \frac{\eta}{\pi r^2} \frac{\phi}{H} \qquad (2)$$

If instead of a single capillary tube a porous diaphragm is used, which is equivalent to a bundle of n tubes of radius r with a total cross-section $s = \eta \pi r^2$ giving a flow of $\Phi = \eta \phi$, we obtain

$$\sigma d = \frac{\eta}{s} \frac{\Phi}{H}, \text{ or } \Phi = \frac{\sigma d}{\eta} Hs \qquad (3)$$

Sometimes one introduces in this formula the difference in potential ζ, or "electrokinetic potential", between the two phases of the double layer and the dielectric constant D (or specific induction power) of the liquid.

These two phases can indeed be considered as the two plates of a condenser, the dielectric of which would be constituted by a sheet of the liquid of thickness d; the capacity by unit of surface of such condenser would be $\frac{K}{4\pi r}$, and by definition

$$\sigma = \zeta \frac{D}{4\pi d}$$

hence

$$\sigma d = \zeta \frac{D}{4\pi}$$

By carrying this value in expression (3), one finds:

$$\phi = \zeta \frac{D}{4\pi\eta} Hs \qquad (4)$$ [3]

For the applications let us eliminate H by introducing the density of current j in the liquid crossing the capillaries, and the resistivity ρw of this liquid. If U is the difference in potential applied at the ends of the n tubes of total cross-section s, one has

$$H = \frac{U}{L}$$ (In volts per cm. for instance).

and on the other hand

$U = RI$, R being the electrical resistance of the liquid equal to $\rho w \frac{L}{s}$ and

$I = js$: the total intensity crossing the liquid.

Hence

$$H = \frac{U}{L} = \frac{Rjs}{L} = \rho w j \qquad (5)$$

Combining this value of H with equation (4), [4] one finds:

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[3] This electrical resistance should take into account the filtration electromotive force which seems to act as a counter-electromotive force in the phenomenon of electrophoresis.

4/ Op. cit.

$$\emptyset = \zeta \frac{\rho w D}{4\pi\eta} js$$

It is seen that according to the laws that were established by way of experiment the electro-osmotic flow is proportional to:

1) the density of current j

2) the net cross-section s of the porous diaphragm

3) the electro-osmotic resistivity of the liquid

4) the inverse of the viscosity of the liquid

5) the electrokinetic potential ζ and the dielectric constant D of the liquid.

It is independent of the length of the capillary tubes, which will however be brought in to determine the difference in potential U necessary to produce the total current js.

b) Electro-osmosis

Let us consider a single particle in suspension in a liquid within an electric field H. If the particle was kept from moving the liquid would slide along its surface; but the particle not being immovable, it will travel in the opposite direction and will soon acquire a uniform motion. It is natural to admit that the relative velocity u of the two electric layers of contact is the same as if the particle was maintained still. The equation (1) previously established may be kept:

$$\sigma d = \eta \frac{u}{H} \qquad \text{hence} \qquad u = \frac{\sigma d}{\eta} H \qquad (6)$$

In a slightly more concrete way it is possible to reason as follows. Let q be the electric charge carried by the particle. Due to the electric field it will be subjected to a charge:

$$F = qH$$

Under the influence of this charge the particle will set in motion to reach a constant velocity when the frictional force f due to the viscosity of the fluid crossed by the particle will become equal to the action of the electric field. Owing to the small velocities in play f may be determined by the formula close to Stokes'

$$f = 6\pi r\eta u$$

r being the radius of the particle.

For F = f one will have

$$qH = 6\pi r\eta u$$

hence

$$u = \frac{qH}{6\pi r\eta}$$

(6a

The formulas (6) and (6a) (in which H could be replaced by $\rho_w j$, as it was done for electro-osmosis) show that the velocity of migration of a particle is proportional to the electric field applied and inversely proportional to its radius and the viscosity of the liquid.

c) - Electromotive force of filtration

Let p be the difference of pressure at the ends of a capillary tube of length l. The laws of hydraulics show that the velocity at the wall v in such a tube is given by the formula

$$v = \frac{r}{2\eta}\,\frac{p}{l}\,d \quad \text{(Poiseuille)}$$

The uniform motion of the electric layer carried along by the liquid produces a convection current 5/

5/ It is really a convection current since the molecules of water of the layer are the material vehicles of the electric charges, whose motion constitutes the electric current considered. In the conduction currents, which appear in metals, for instance, it is admitted that the electrons are the convoying agents of the electric charges.

$$i = 2\pi r v \sigma$$

which, if replacing v by its value, becomes

$$i = \frac{\pi r^2}{\eta} \frac{p}{l} \sigma d$$

When a permanent flow has been established, provided that the wall is insulating, this current must balance the conduction current produced in the liquid by the sought electromotive force E of filtration; This current i' has evidently the value:

$$i' = \frac{E}{\rho w} \frac{\pi r^2}{l}$$

Let us write i = i'

$$\frac{E}{\rho w} \frac{\pi r^2}{l} = \frac{\pi r^2}{\eta} \frac{p}{l} \sigma d$$

or

$$\frac{E}{\rho w} = \sigma d \frac{\rho}{\eta} p$$

Hence

$$E = \sigma d \frac{\rho}{\eta} p \tag{7}$$

This review of the essential principles of electro-osmosis and related phenomena will here come to an end. For further detail the reader is referred to the specialized works (see brief bibliography at the end of the present paper). It is possible that the above-mentioned theories are not concretely exact and constitute only a symbolism that would enable a simple representation of very complex problems. It is none the less, for the engineer, a tool of computation and of prevision giving results generally proved with a sufficient approximation by experience.

Already it is interesting to emphasize that the analyzed phenomena are of a magnitude that may be considerable for small consumption of electric energy; whereas in electrolysis the substance is carried in the state of ions, which requires approximately 27 amperes-hour (96,600 coulombs) per valence gram (which, taking into account the electromotive forces generally used, corresponds to a depositing of 2 kilograms of matter per kilowatt-hour at the maximum), in electrophoresis an ion transports the weight of matter represented by the particle that absorbed it, which weight is much more considerable than the weight of the ion.

Finally, the ratio of the efficiency of such operation to the efficiency of electrolysis is proportional to the size and density of the particles in suspension carried along by the ions.

Theoretically if no secondary phenomena occured, this ratio could reach a value of the order of a million; practically, in good laboratory conditions, values of the order of 1,000 or 2 tons per kilowatt-hour were attained. 6/

But if the liquid is made to be a good conductor by the presence of electrolytes, the electric energy is for the most part used by the electrolysis and the efficiency becomes very poor.

II. Research of the soil mechanics laboratory of "Ecole polytechnique" of Zurich

a) Theoretical studies

With a view of applying the phenomena of electro-osmosis to soil mechanics, MM. W. Schaad and R. Haefeli resumed as follows the results of the theory of Helmholtz-Perrin-Smoluchowski which has been outlined in the preceding chapter.

Let us consider a capillary tube (fig. 1) of length l and of non-conducting material, subjected at both ends to a hydrostatic pressure $p = \gamma_w h$ and to a difference in potential U which produces in the tube an electric current of intensity i. According to formula (5) the mean velocity u of the fluid within the capillary tube will be:

$$u = \frac{r^2}{8\eta} \frac{p}{l} + \zeta \frac{\rho w D}{4\pi\eta} j \qquad (8)$$

This equation may be given in the form

$$u = u_0 + u_1 \qquad (9)$$

where u_0 is the velocity of the laminary flow (given by Poiseuille formula) which would be established in the absence of any electric

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6/ This has made possible the industrial application of electrophoresis for the treatment of materials of low commercial value, such as kaolin, ochres, peat, gases from metallurgic furnaces, smokes, etc.

phenomenon owing to the hydraulic head $h = \frac{p}{\gamma w}$, and u_1 is the velocity due to the electro-osmotic action only.

For the above equations to be applicable to the flow of a liquid in a permeable fine-grained mass, the mean velocity u may be replaced by the "total velocity of filtration" V_F referred to the total flow area of the porous mass. The equation (9) is then written:

$$V_F = V_D + V_E = kj + k_E D \tag{10}$$

where

V_F = total filtration velocity

V_D = total filtration velocity according to Darcy law

V_E = electro-osmotic velocity of filtration

k = the coefficient of permeability according to Darcy

J = hydraulic gradient

E = electric field intensity

k_E = the electro-osmotic coefficient defined as being the velocity produced by a field intensity E of 1 volt per cm.

In practice the electro-osmotic coefficient depends upon numerous characteristics of the porous aggregate and of the liquid which flows through it: coefficient of porosity, electrical resistance (galvanic and electro-osmotic) of the solid and of the liquid, viscosity and dielectric constant of the liquid, etc.

The value of k_E which characterizes the porous material with respect to the electro-osmotic action can be measured directly by laboratory tests, as it will be seen below. As a matter of fact, it appeared more practical and more suggestive to determine the "electro-osmotic head" H_E or the "specific electro-osmotic head" h_E. According to fig. 2, the first one H_E is defined as the head in cm which is produced by the tension of 1 volt applied to a sample of the material tested in an apparatus and according to the standardized methods. When this charge is attained in the testing appartus of fig. 2, a state of equilibrium (no flow) is attained which shows that the electro-osmotic pressure balances the hydrostatic pressure. Then $V_F = 0$ and

$$J = \frac{H_E}{L}$$

consequently equation (10) is written

$$V_F = - kJ \div k_E E = - k \frac{H_E}{L} \div k_E \frac{U}{L} = 0$$

L being the length of the sample

In consequence one has

$$H_E = \frac{k_E}{k} U = h_E U \qquad (11)$$

The ratio $\frac{k_E}{k}$ represents the "specific electro-osmotic charge" h_E expressed in cm. per volt. 7/

7/ Indeed the coefficient of permeability k is expressed in cm. per second, whereas the electro-osmotic coefficient k is expressed in cm/sec. per volts/cm.; consequently h, ratio of these two quantities, will be expressed:

$$\frac{\text{cm./sec.}}{\text{volts/cm.}} \cdot \frac{1}{\text{cm/sec.}} = \text{cm. per volt}$$

Carrying this value of h_E in equation (10) one obtains:

$$v_F = k\left(J + \frac{k_E}{k} E\right) = k\left(J + h_E E\right)$$

equation which shows that h_E characterizes the increase of filtration velocity v_F which may be obtained by applying a field of E volts per cm. to a ground flow which was determined previous to any exterior electric action, by its coefficient of permeability k and its hydraulic gradient J. The parameter h_E may consequently be taken as measure of the electro-osmotic effect.

In the applications of electro-osmosis to the drainage of soils the above-mentioned simple calculations are not sufficient because the distribution of the lines of hydraulic and electric currents has to be considered in a three or eventually two-dimensional area.

The general differential equation of flow is then (in c.g.s. units):

$$k\Delta \phi_H \quad D_B \Delta \phi_E = - 4\pi\varepsilon \qquad (12)$$

Δ is the operator of Laplace

ϕ_H the potential of the hydraulic field of the ground flow

D_B the dielectric constant of the saturated ground;

ϕ_E the potential of the electric field

ε the density of electric charge per volume unit.

The application of this equation to concrete cases is quite laborious because the lines of current of the hydraulic and electric fields and also "their conditions at the limits" generally do not coincide; equation (10) must then be considered as a vectorial equality. The total flow Q_E transported by electro-osmosis always remains in the form

$$Q_E = k_E \rho_w I$$

I being the total intensity in the ground.

The application of the above-mentioned methods to the simple drainage device shown in fig. 3, which includes two electrodes vertically driven into a water bearing soil led to the following results:

Electric resistance between the two electrodes:

$$R \# \frac{\rho_w}{\pi +} \operatorname{Log}_e \left(\frac{s}{r}\right) \quad \text{in ohms} \tag{13}$$

Intensity:

$$I - \frac{U}{R} \# \frac{\pi U t}{\rho_w} \frac{1}{\operatorname{Log}_e s/r} \quad \text{in amperes} \tag{14}$$

Electro-osmotic flow

$$Q = k_E \rho_w I \# k_E \pi U + \frac{1}{\operatorname{Log}_e s/r} \quad \text{in } cm^3/s \tag{15}$$

ρ is the resistivity of the soil in the saturated state

t the length of the section of the electrodes driven into the ground water

s the interval between electrodes

r the radius of the electrodes

U the difference of potential applied between the electrodes

b) Laboratory tests

The purpose of these tests was to check the validity of the laws of electro-osmotic filtration within fine-grained pulverulent masses and to perfect a measuring method of the electro-osmotic coefficient k_E and of the specific electro-osmotic head h_E of a given material.

The apparatus shown on figs. 4 and 5 was used (oedometer suitably modified). The soil sample is held in a glass cylinder between two pistons of rigid plastic material perforated with holes and carrying two perforated electrodes of platinum (to prevent electrolytic corrosion); the bottom of the lower piston is inclined in order to facilitate the adduction toward an exhaust-pipe ad hoc of the gas which could eventually be produced by electrolysis. The apparatus may be used following two different methods.

1. Measurement of the electro-osmotic flow

If the apparatus is set in such a way that the level is the same at the inlet and the outlet (fig. 4) one has $J = 0$, and equation (10) gives:

$$V_E = k_E E$$

In the conditions of symmetry brought in the electric field $E = -\frac{d\phi_E}{ds}$ is constant over the whole length of the sample and equal to $\frac{U}{L}$; hence

$$k_E = v_E \frac{L}{U}$$

v_E is determined by measuring the volume V of flow during a given time and by dividing it by the section F of the sample.

2. Measurement of the pressure (head of water) produced by electro-osmosis without flow

The electro-oedometer is set as shown on fig. 5.

The electric connections are in the opposite position of fig. 4 so that the electro-osmotic flow runs from top to bottom. The water supply-pipe is replaced by a graduated tube of sufficient height.

Figures 2 and 5 show how to measure the electro-osmotic head H_E from which the specific electro-osmotic head is deduced $h_E = \frac{H_E}{U}$

As it was shown that

$$H_E = \frac{k_E U}{k} = h_E U$$

the electro-osmotic coefficient k_E can be computed if the coefficient of filtration k (which is determined with the same apparatus but leaving out the electric field) is known.

To show the importance that H_E may have in certain soils, the measurements made on a silty sand of coefficient of filtration k = approx. 10^{-7} cm/s. are summed up below:

The test was to be made according to method 2 (without flow)

In the course of the first part of the test carried out during 8 hours under a constant intensity of 10 milliamperes, the height H_E in the piezometric tube passed progressively from 0 to 28 cm. approx. (the necessary voltage increasing correlatively from 10 to 19.4 volts approx.)

In the second part of the test, quite irregular, the intensity fell little by little below 4 milliamperes, when the feeding tension was of the order of 27 volts; after 4 days the height H_E attained 1.50 m., the limit of measuring possibilities of the apparatus.

The electro-osmotic coefficient k_E was then calculated from the filtered flow under the mean tension of 14.7 volts in the first part of the test. It was found that:

$k_E \# 8.7 \times 10^{-6}$ cm/s per volt/cm

Wherefrom:

$$h_E = \frac{k_E}{k} = \frac{8.7 \times 10^{-6}}{10^{-7}} = 87 \text{ cm per volt}$$

For the mean tension of test of 14.7 volts the following result would have been attained if the experiment had been continued during a time long enough to obtain no flow:

$$H_E = h_E U = 0.87 \times 14.7 = 12.80 \text{ meters.}$$

An electric field of 1 volt per cm will produce in this soil an increase of filtration velocity of

$$87 \times 10^{-7} \text{ cm/s}$$

which is considerable if one notes that the natural filtration would give for a gradient of the water table $J = 1$ only 10^{-7} cm/s.

The laboratory of Zurich also studied the electro-osmotic characteristics of a powder of quartz (grains of 0.002 to 0.2 mm : $d_{50} = 0.13$ mm), which was used by the said laboratory because of its resistance to chemical agents.

For this material, it was found that:

$$k_E = 4.5 \cdot 10^{-5} \text{ cm/s per volt/cm}$$

$$h_E = 12 \text{ cm per volt}$$

$$K = 3.7 \cdot 10^{-6} \text{ cm/s}$$

Because of the greater natural permeability of the material, the electro-osmotic head per volt

$$h_E = \frac{k_E}{k}$$

is smaller than in the preceding case in spite of a higher value of k_E

c) Field tests

The laboratory of Zurich made a test of electro-osmotic drainage in a silty sand soil by using the setup shown on fig. 6. The electrodes were constituted by ordinary 22.7 mm gas pipes fed in direct current by a welding set of variable voltage. Before switching on the current, the water level in the well connected to the negative electrode was lowered by pumping; the test consisted in measuring the upward motion of water as a function of time with and without circulation of electric current after pumping had stopped.

Figure 7 gives the result of such test made with electrode intervals of 6.25 m - 6.35 m and a current of 64 volts. It will be seen that, owing to electro-osmosis, the level in the well at the end of the test exceeds by approx. 0.40 m that of the ground water, and particularly that the speed of water rising in the well is four times faster when switching the current on the electrodes. This shows the increase in filtration capacity of the soil which is produced by the electro-osmosis effect. The total resistance of the testing device was of approx. 40 ohms and the current delivered 1.6 to 1.7 amperes, so that the consumed power did not exceed 100 to 110 watts. The mean electro-osmotic flow was of the order of 0.1 cm^3/s.

On the other hand, using the above-mentioned formulas (13), (14), (15) the values of R, I and Q were computed starting from the following soil characteristics (determined in the laboratory):

Soil resistivity $\rho = 4,570$ ohms/cm

Electro-osmotic coefficient $k_E = 8.7 \times 10^{-6}$ cm/s per volt/cm

The computed results and the observed results are barely different and show that the above-explained theory makes it possible to estimate a priori the order of importance of the main parameters.

III. A few instances of practical application of electro-osmosic drainage of fine-grained soils.

a) General - The following information is in the main taken from the above-mentioned L. Casagrande's paper. Dr. Casagrande is the promoter of the application of electro-osmosis to the drainage of unconsolidated soils with a view of carrying out earthwork or foundation works. Before becoming one of the collaborators of the Building Research Station in London, Dr. Casagrande made in Germany in the last few years diverse theoretical studies and several large-scale applications of the process.

According to this author, the electrical drainage should be used when the grain size of the soil is too fine for the usual methods to be applied; this occurs approximately in soils where the greater proportion of particles has a size of less than 0.02 mm. If drainage wells provided with a negative electrode are installed in such soils, the moisture in the soil will be compelled to flow to these wells, from which it will be removed by the usual methods. Electro-osmosis makes it possible to drain to any extent that is desired soils such as silt, loess and all kinds of clay and loam.

Although the extensive electrical drainage of clay seems expensive, experience has shown that its application in the case of silt soils is economical and more effective. These soils have a low cohesion and when they are in a saturated state they flow even on very flat slopes; in excavations they have a tendency to uplift and to flow in the manner of quicksand under the action of a very low hydraulic underpressure.

It has been shown that in practice the reversing of the direction of the flow of water in such soils, even without any marked reduction of the moisture content, is sufficient to prevent the above-mentioned phenomena.

The flow of water to be drained in order to obtain the reversing of the direction of the flow is generally very small in absolute amount.

Figures 8 and 9, which give the flow net in a cut slope saturated by a continuous rain, show clearly the stabilizing effect of a drainage well of depth 1.5 times the height of the cutting and which was dig slightly back of the slope.

Of course, this stabilizing effect is obtained whatever the method used to assure the filtration of the ground water toward the well, but in a very fine-grained soil, electro-osmosis only will make it possible to obtain a suitable coefficient of filtration.

Figures 10 and 11 show in the same way how a row of drainage wells placed behind a sheet piling protecting an excavation prevents the uplift of the floor of the excavation under the effect of underpressures.

After making systematic laboratory tests on 26 types of soils of varying composition from pure silt to fat clay, Dr. Casagrande was able to carry out during the war large-scale applications of his process. Following is a brief description of some of the most interesting of these applications.

b) <u>Railway cut near Salzgitter</u> - A double-track railway cutting was to be made in an unconsolidated loess-loam deposit. Although it was only 7 m. deep the construction of slopes was impossible even in dry weather since the high level of the ground water caused the soft soil to flow out when the depth of the cutting was barely 2 m.

The first test of drainage was made on a stretch of 100 m. On the basis of the results obtained in the laboratory in the model test it was decided to install 10 well electrodes (7.5 m long and 10 cm in diameter) spaced at intervals of 10 m along the top of the stretch to be tested and on each side of the cutting. Rod electrodes comprising a length of 1 cm diameter gas piping (7.5 m long) were placed between the well-points. The water flowing to the well-points was collected by small automatic pumps, each pump servicing two wells and transported through a common pressure pipe in two measuring centers where the water was carefully collected in large containers, and records were kept of any possible fluctuations in the amount of water flowing in.

Before the electric current was switched on, the water flowing to the 20 wells did not exceed 0.4 m^3 in 24 hours. Only a few hours after switching on the D.C. current at 180 volts and an average of 19 amps. per well, the flow of water rose to many times that of the amount obtained before. Over the time required for the construction of the test stretch (8 weeks approximately) the amount of water was collected at an almost constant rate of 2.5 m^3/h. for all 20 wells together. Thus in 24 hours about 150 times the amount of water than was obtained without the action of the current.

In order to save the current the voltage was reduced to 90 volts when the floor of the cutting was reached. It was found that the rate of flow of the water was materially reduced. If the current was switched off altogether the rate of flow was substantially reduced only after a period of about 6 hours, but was reduced to the amount obtained before electrical treatment only after 24 hours.

The results of this drainage on the holding of the soil were excellent. Whereas before the application of osmosis the excavator could not be placed near the cutting as it would have tilted or sunk into the soil, it was found that after the application of the method the excavator could be used wherever it might be desired. Slopes, which before could not even be constructed at a gradient of 1:3, could now be dug at a gradient of 1:0.75. The supply of current to some individual wells was temporarily interrupted for testing purposes. It was found that after more than 6 hours a soft mass of soil began to flow out of the slope within the region of the cut-off wells. If the wells were once more included in the electrical circuit the flow phenomena would cease after a short period. Following the large-scale test the entire length of the cut of several kilometers was constructed in the same manner. Further, no difficulties were encountered in the removal of the soil.

c) Bridge foundations at Saltzgitter

Composition of the soil: loess loam

Depth of the excavation: approximately 6 m.

Dimensions of the foundations: 8 m x 15 m

Drainage by 6 well electrodes similar to those previously described and supplied by a 90 volt current.

The excavation could be carried out with almost vertical walls.

d) U-Boat Pen, Trondhjem

Composition of the soil: clayey silt, interspersed now and again by a seam of sand.

Depth of the excavation: 14 m.

Surface: 230m x 160 m.

The site was in the proximity of the sea and the groundwater level was only a few meters below the surface. In spite of a protection of a double row of sheet piling and low slope gradients, it was impossible to continue the construction works owing to the bad holding of the ground (distortion and horizontal displacement of the piling in spite of a 15 m hold; uplift of the floor of the excavation, etc.)

The silt deposited near the coast contained salts which considerably reduced its resistivity so that a large amount of current would be required.

After several tests with voltages ranging from 10 to 200 volts, it was decided to adopt a tension of 40 volts. At this voltage the consumption of current was between 20-30 amps. per well.

The drainage device included two rows of well-electrodes which were fitted all around the excavation on a berm about half way up the slope. The wells had a diameter of 25 cm and a depth of 20 m. and were spaced at 10 m. intervals. Each well was serviced by its own automatic pump, which in turn was connected to a common pressure pipe.

The amount of water pumped up in the various parts of the excavation varied considerably, owing to the irregular composition of the ground. Before the application of electrical current it varied between 1. and 50 l. per hour and per well. After switching on the current the rate of flow from each well increased to 11 to 470 l./hour. The excavations were carried out without difficulties and the average energy worked out at about 0.4 kw.hr/ cu.m. of soil excavated.

e) Tunnel cut in the Lerkendal Valley

This railway tunnel located near Trondhjem was to cross a deposit of very soft clayey silt having a moisture content of between 18 and 37 percent on dry weight and a liquid limit of between 25 and 30 percent. The construction of an open cutting of a depth up to 19 m. was not considered practicable and the shield construction method seemed the only right and possible method. But in order to speed up the rate of construction it was decided to resort to the construction of a tubular tunnel in an open cut with the help of electro-osmosis, the cutting being filled in again after the completion of the project. On either side of the cut, which was to have 1:2 slopes, approximately half way down on a berm of a width of several meters, two rows of well electrodes with diameters of 276 mm. were sunk down to 2 m. below the projected depth of the cutting. They were placed at intervals of 10 m. Gas piping of equal length and ½ inch in diameter constituted the positive electrodes which were driven in between the cathodic wells and at the same depth. The tension was 30 volts; the current consumption was on the average 15 amps. per well. Without the action of electric current the wells did not collect any appreciable amount of water; but after the current had been switched on the amount of water was on the average of 120 l./day per well.

f) Other applications

L. Casagrande mentions tests of drying industrial wastes at Wulfrath. Reductions in moisture content of the order of 10 to 20 per cent of the original value may be obtained without difficulty and with an economic current consumption. A much more intensive drying may be obtained but the consumption of current and the length of the treatment increase considerably.

B. A. Rzhanitzin has published a study on tests made in Russia on the "Electro-chemical stabilization of clay soils". This method seems to use together the electro-osmosis and the electrolytic substitution of certain bases more resistant than certain salts existing in soils for the formation in situ of ferric or aluminous gels. The cathodes are of copper and the anodes of aluminum and solutions of $CaCl_2$ or NaCl are injected.

Tests were made in Russia to check up and reduce the swelling of clayey soils on thawing, by the effect of electro-osmosis on the rising of water in these soils.

MM. Schaad and Haefeli have shown the interest that would have the electro-osmotic injection in soils which are too fine to be consolidated by the usual methods.

Conclusion

The preceding report shows that the phenomena of electro-osmosis, which seemed to have to remain in the scope of the laboratory or of some physico-chemical manufactures, have found a few interesting applications in public works. Investigations are carried out abroad with a view of extending their utilization to the injections for consolidation of fine-grained soils, to the improvement of some building materials, to the drainage of damp masonry masses, etc. It is to be desired that the French engineers follow this example.

As far as the author is concerned, he has studied the possibility of applying electrophoresis to the accelerated decantation of large volumes of water containing silt or very fine sands. The classical sand-removing devices installed in the neighborhood of water from hydroelectric plants or of irrigation ditches are unable to precipitate particles of sizes smaller than 0.1 or 0.2 mm.; in some particular instances, the elimination of such fine elements would however be desirable.

The already old industrial applications of electrophoresis to the purification of clay (kaolin) and to the removal of dusts from gases constitute inducing precedents. If it is admitted, by comparison with results from industrial electrophoresis operations that 1 kg. of material 8/ can be deposited per amp./h., it seems a priori possible, by using electrodes of large area and sufficiently close to each other, to eliminate almost all the particles (assumed to be very fine) in suspension in a discharge of 1 m^3/s with turbidity of 1 o/oo, 9/ by means of a silt remover consuming a power of 40 kilowatts under about 10 volts.

The first tests made by the author on suspensions of 1 o/oo kaolin or of fine muds show that the used device assures an accelerated sedimentation of the particles contained in water; unfortunately the phenomena of electrolysis concomitant to electrophoresis consume a large amount of current.

8/ This is, it seems, a very moderate amount; industrial tests of drying peat by electro-osmosis would have shown that a given current intensity displaces 5,000 times more water than it could decompose by electrolysis.

9/ Very high amount if it is admitted that the large particles are previously eliminated by a classical gravity sand remover.

The result is an efficienty much lower than that obtained in the experiment above. Tests are being continued for the purpose of reducing the consumption of current by electrolysis without affecting the efficiency of the electrophoresis process.

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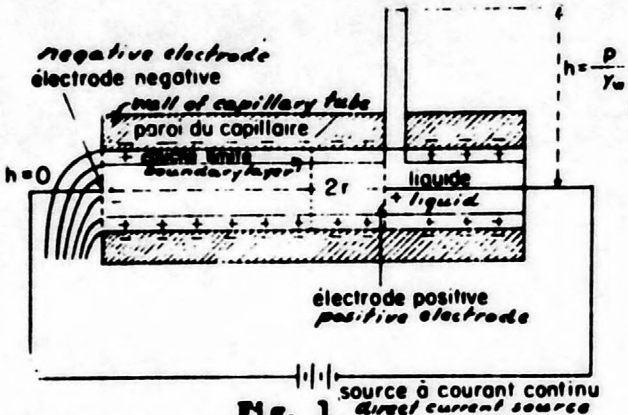

Fig. 1
Hydro-electro-osmotic flow within a capillary tube.

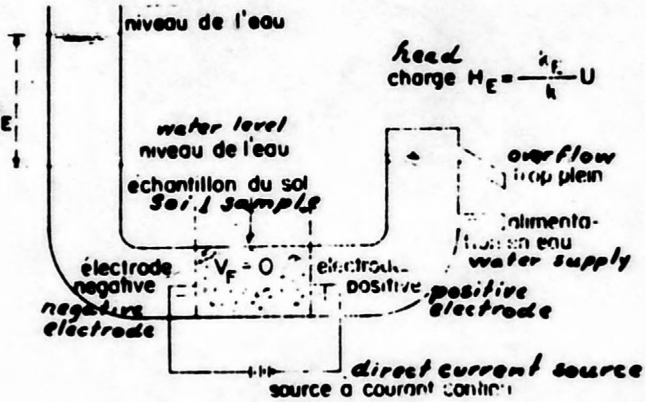

Fig. 2
Principle of measuring the electro-osmotic ~~charge~~ head H_E.

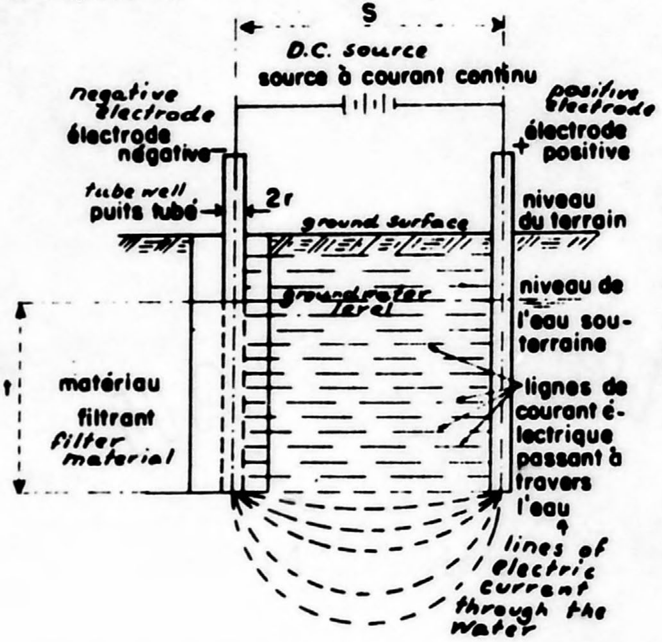

Fig. 3
Sketch of electro-osmotic drainage well.

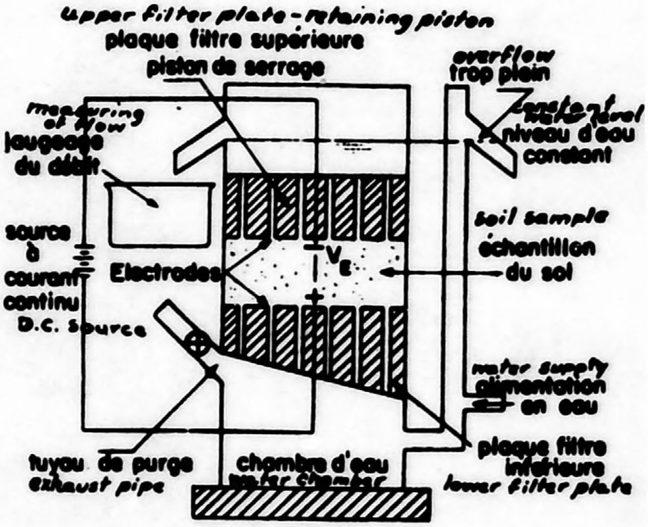

Fig. 4
Apparatus for measuring electro-osmotic flow.

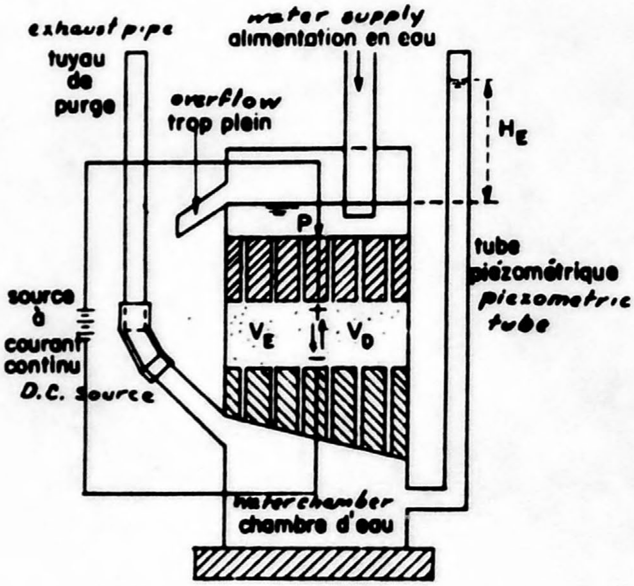

Fig. 5
Apparatus for measuring the electro-osmotic static head.

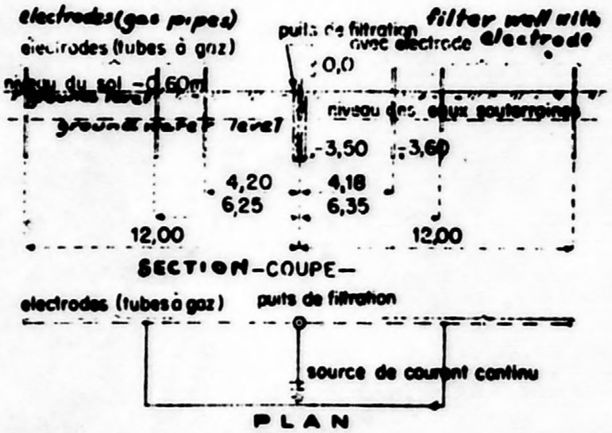

Fig. 6
Test of electro-osmotic drainage well.

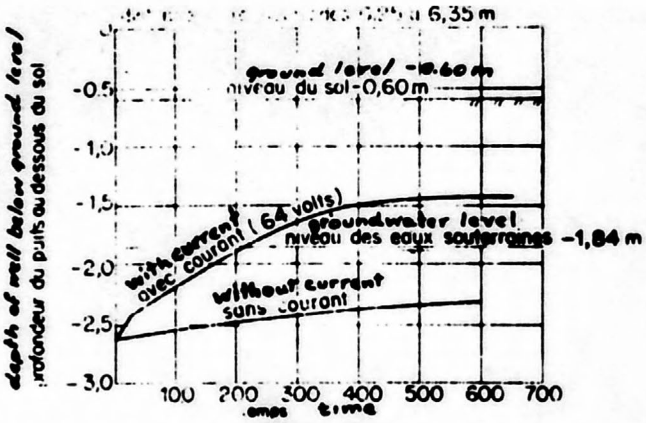

Fig. 7
Results of tests made with arrangement shown in fig. 6.

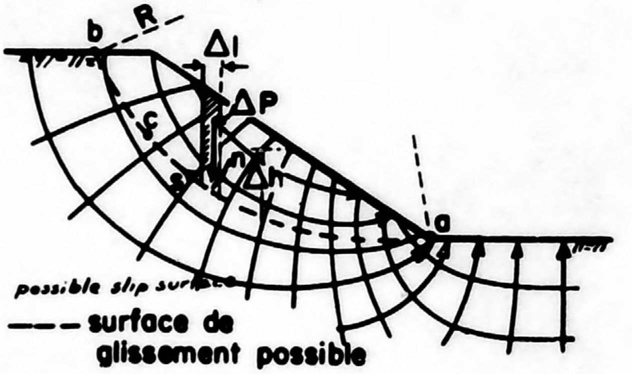

Fig. 8
Flow net in a cut bank during a period of continuous rain.

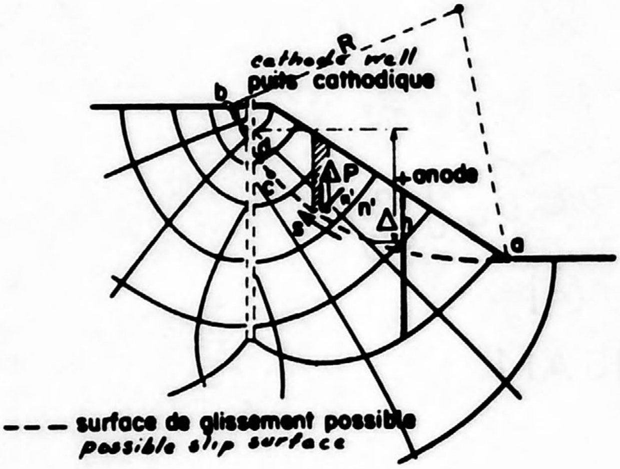

Fig. 9
Effect of an electro-osmotic well on flow net shown in fig. 8.

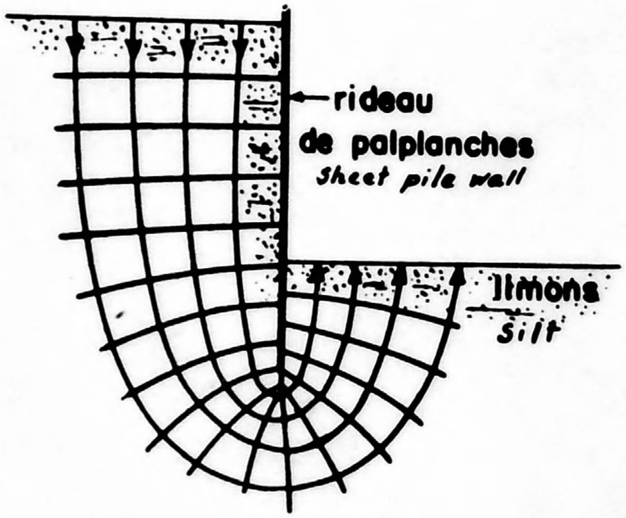

Fig. 10
Flow net near sheet pile during a period of continuous rain.

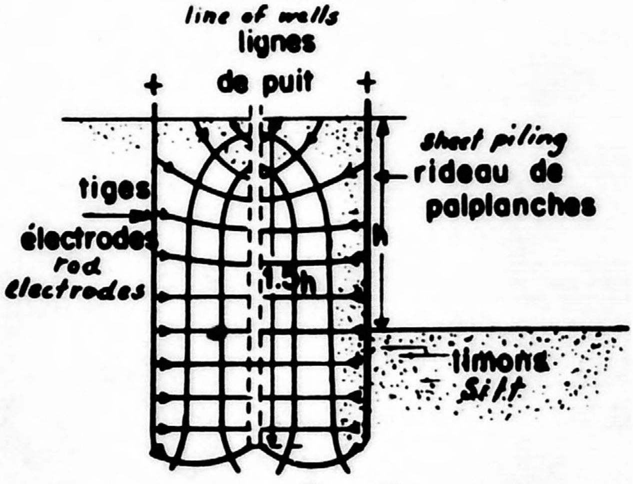

Fig. 11
Effect of electro-osmotic well on flow net near sheet pile wall shown in fig. 10.

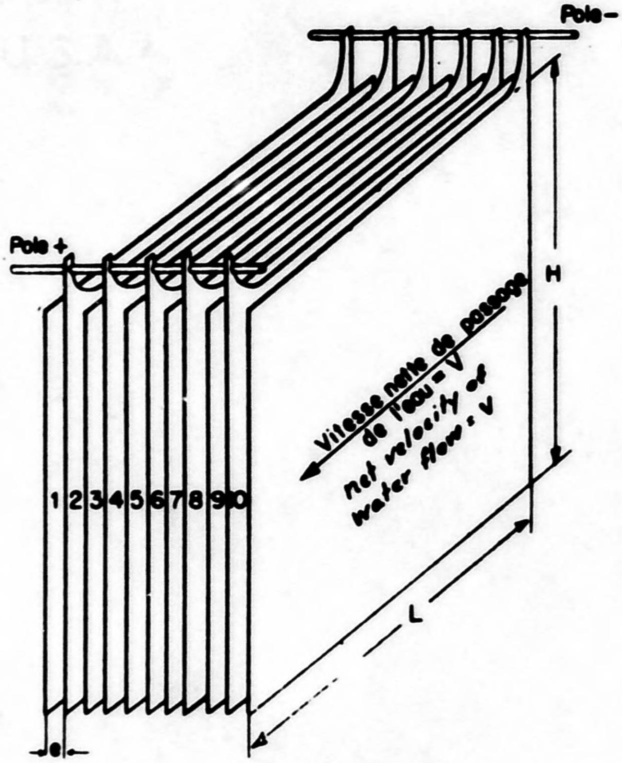

Fig. 12
Sketch of an electric silt remover