ELECTRICAL DRAINAGE IN SOIL STABILIZATION

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In military engineering operations, the need for stabilizing plastic soils particularly at strategic points often arises in order to improve the trafficability of soils for army vehicles and tanks. The usual method of ground water lowering by the well point system is applicable only to sandy soils and the method does not work in the case of silty and clayey soils. The method of electrical drainage has been worked out both on the laboratory and field scale and is found to be quite successful in cases in which there is no alternative method of stablization. Normal drainage in clayey soils is not practicable owing to the fact that the power of the clay to retain water is greater than the pull exercised by gravity. Besides the rate of permeability is very low.

Electrical drainage is the process of promoting drainage by applying electric field to soil and is based upon the application of electroosmosis. Electroosmosis is the movement of a liquid in a porous medium under the influence of electric field (16) and it can be applied to the removal of water from soil.

Electroosmosis

In a capillary filled with water the interface between the liquid and solid is the seat of electric potential produced by the formation of Helmholtz electric double layer. When an electric potential is applied between the two ends of the capillary, water begins to flow. The flow of water through the capillary is given by the modified Helmholtz equation (8):—

$$Q = \frac{EDr^2\zeta}{4\eta l}$$

Where Q=quantity of water flowing per second.

D=Dielectric constant of water.

r=radius of the capillary.

ζ=zeta potential *i.e.*, potential of the double layer.

η=viscosity coefficient.

l=length of the capillary.

If applied to a bundle of capillaries of cross sectional area A as in soils the corresponding electroosmotic flow is given by the equation:—

$$Q = k_e \quad i_e. A$$

where K_e is the coefficient of osmotic permeability (cm per second per volt per cm.) which depends upon porosity and zeta potential.

$i_e.$ is the electric gradient in volts per cm.

Electroosmotic permeability

For a given soil of unit cross section electroosmotic permeability is given by Haefeli and Schaad(9)

$$V_e = K_e E$$

where V_e is velocity of flow in cms/second.

K_e is the coefficient of electroosmotic permeability in cm per volt per second and

E is the electric potential gradient U/d where U is electric tension between electrodes in volts, d is distance between electrodes.

Hydraulic permeability

For the same soil, Hydraulic permeability is given by Darcy's law(9)

$$V_o = Ki$$

where V_o=velocity of flow in cm per second.

K=coefficient of hydraulic permeability in cm/second and

i=the hydraulic gradient

Total hydraulic and electroosmotic permeability acting at the same time is given by

$$V = V_o + V_e = Ki + K_e E$$

Schaad (13) has made an analysis of the results of Casagrande and other workers on electroosmosis and has discussed the limitations of Helmholtz formula. The results of experiments show that the flow decreases with increase in diameter of the capillary whereas Helmholtz formula indicates just the opposite effect, that with a capillary of infinite diameter, the electroosmotic flow should also be infinite. Schaad points out that Helmholtz formula neglects the other effects such as electrolysis and conductivity of soil particles which also occur simultaneously. The total current is thus to be divided into (1) galvanic phase current transporting ions (2) surface current transporting charges of double layer (3) current flowing through solid particles. He further points out that in laboratory experiments on electroosmosis disturbance of electroosmotic effect by electrolytic decomposition of the liquid and electrodes is considerable. During the test, polarization of the electrodes, increase or decrease of electrical resistance and exchange of ions between liquid and soil, inversion and oscillation of flow, increase in acid and basic concentration and change in electrokinetic potential of double layer were observed. Schaad however points out that the above influences are less evident and less important on large scale and field experiments than in laboratory tests. Experience with filter wells showed that several days of flow of current did not change the electroosmotic discharge at the well point.

Casagrande's apparatus (2) used for the study of electroosmosis in the laboratory has been shown in Fig. 1. It consists of a rectangular

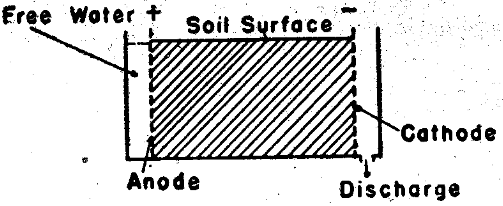

Fig. 1—Apparatus used by Casagrande in his work on electroosmosis

block of soil with perforated sheet electrodes at the two opposite faces. MacLean (6) has used a cylindrical block of soil with two disc electrodes. In studying electroosmotic effect it is necessary to avoid heat effect by sending low currents. Water flows to cathode. In electrical drainage, the cathode consists of a perforated tube. As water collects in the well point tube it can be periodically pumped out.

Electroosmotic pressure

In an electroosmometer it is possible to prevent the electroosmotic flow of water to the cathode by applying a suitable hydrostatic pressure. In any particular system, for a definite electrical potential, the hydrostatic pressure that is just sufficient to prevent electroosmosis is known as electroosmotic pressure. Casagrande (2) and Geuze, Bruyn and Joustra (9) have described laboratory models of a electroosmometer. According to Geuze and co-workers, the electroosmotic rise in a tube is given by

$$H=\frac{K_e}{K}U$$

where U is the electrical tension between the electrodes in volts.

Electroosmotic studies have also been made by Barber (1). He has given the formula for the osmotic flow

$$V=\frac{tA}{K}\,\frac{CE}{L}$$

where V=quantity of water transported.

t=time

A=Cross section

K=resistance to flow of water.

C=charge.

$\frac{E}{L}$=voltage gradient.

This is similar to the relation between normal flow and hydraulic gradient.

Substituting RI for $\frac{AE}{L}$ where R=resistivity, I=current.

$$V=\frac{t\,CRI}{K}$$

The quantity of water flowing is proportional to the quantity of electricity. This relation is true for low current densities until there is excessive drying at the anode.

Having dealt with the theory of electroosmosis, some of the important generalizations deduced from experimental investigations may now be considered.

Electroosmotic current in relation to particle size

Though the osmotic effect depends primarily upon the potential gradient, the current flowing is conditioned by the type of soil and the electrolytic content. According to Casagrande the amount of current passing per square centimeter of soil depends largely on the grain size(2). Fig. 2 shows a gradation in the amounts of current passing through systems which vary widely in particle size.

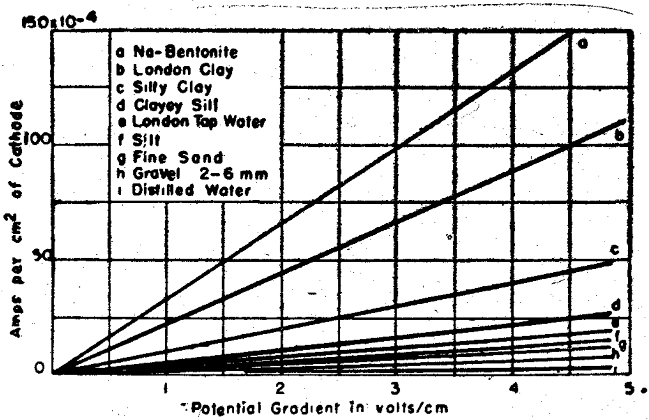

Fig. 2—Flow of current for various soils (after Casagrande)

Coefficients of hydraulic and electroosmotic permeabilities.

Casagrande (2) determined the electroosmotic permeabilities of soil materials with hydraulic permeabilities ranging from 1×10^{-11} cm/sec for sodium bentonite to 8×10^{-3} cms/second for mica including fine sand with a coefficient of $2{\cdot}9\times10^{-3}$. It is interesting to note that mica powder has a permeability of one billion times that for bentonite. Inspite of these big differences in hydraulic permeabilities the osmotic permeabilities are approximately the same for most materials Fig. 3. Ke is about 5×10^{-5} cm per second per volt. per. cm.

Electroosmotic flow and quantity of electricity

MacLean (10) has carried out electroosmotic studies with different soils. In any soil, the weight of water expelled is directly proportional to the quantity of electricity passing through the soil up to a limit beyond which the amount of discharge decreases.

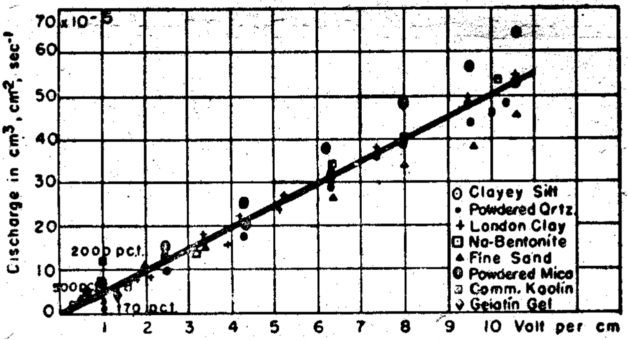

Fig. 3—Discharge of water by electroosmosis (after Casagrande)

Electroosmosis and clay content of soil

The amount of water expelled per unit quantity of electricity has been determined (10). It is the highest for sandy soils and lowest for clays. The quantity of electricity required to expel 1 gm. of water from the soil is dependent upon the clay content of the soil and the relation between the two is linear, Figure 4.

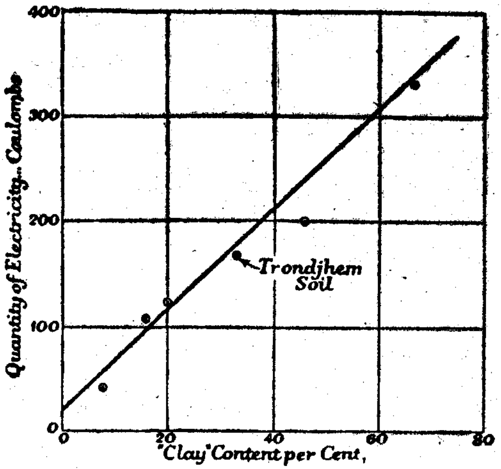

Fig. 4—Clay content and quantity of electricity per gm of soil.

An estimate of this relation in the laboratory will be helpful in deciding the suitability of any soil for electrical drainage.

Electroosmosis and bulk density of soil

MacLean has also found out the influence of the state of compaction of the soil on electroosmotic flow. He states that for relative compactions greater than 95 per cent. the amount of water expelled is the same but at lower compactions the amount of water expelled is lower and variable. This is probably because the soil-water system is not continuous at lower relative compactions.

Moisture gradient in soil between the electrodes at different stages of electroosmosis

The moisture contents in the soil between the electrodes at different stages of electroosmosis have been studied by MacLean and Casagrande. The experiment was continued up to the stage when no more water could be expelled. At any stage in the course of electroosmosis the water content is the lowest at the anode and steadily increases towards the cathode at which water content remains practically the same. As electrical drainage proceeds the decrease in water is small at cathode and increases in an exponential manner to maximum at anode. The fall of water content in the neighbourhood of the anode continues up to the limiting stage when no more current passes through the soil. Electrical drainage is most effective near anode and the drying out of soil is never uniform. This is an important point to be considered in the layout of electrodes in electrical drainage.

Electroosmosis and consolidation characteristics of soil.

Raymond F. Dawson (7) has studied the consolidation characteristics of soil during electroosmosis by employing a consolidometer and has reported certain important generalizations. The passage of current through a soil accelerates drainage which in turn increases the amount and accelerates the rate of consolidation. For any given soil there is a definite amount of electricity required to expel all the water that can be removed by this means. Although increased voltage accelerates the rate of consolidation, it does not increase the amount since all treated soils have equally the same total consolidation for a given load regardless of voltage. Current changes the physico-chemical characteristics of soil near the electrodes.

Development of natural structures and electroosmosis

Casagrande (8) has reported interesting observations on the nature of the changes in structure of the soil during electroosmosis.

Accompanying electroosmosis particularly in clayey soils, Casagrande observed laminations along equi-potential surfaces round the two electrodes and random fissures in the central region. Greater the colloid content of the soil, more distinctly the fissures were developed. Electrodes of different metals were used and microscopic examination of the laminations was also made. The anodic pattern of the laminations when examined under the microscope showed resemblance to the well known Lesiegang phenomenon. The explanation of the development of these laminations and fissures is not yet clear.

Electroosmotic pressure and grain size of soil

Casagrande has determined the hydrostatic pressures developed with different soils, by employing an electroosmometer. Comparing the experimental results with theoretical calculations based on Helmholtz theory—

$$P = \frac{2ED}{r^2}$$

where P=Hydrostatic pressure
E=Potential difference
D=Distance between electrodes
r=radius of capillary tubes

he found that the hydrostatic pressures with fine sand, sandy silt and kaolin derived from direct tests showed fairly good agreement with the theory. However such agreement was not found with soils containing a certain proportion of clay such as clayey silt, London clay and bentonite. For these soils the pressure head developed at the cathode was found to be about 10^3 cm of water for a potential of 20 V. This water head corresponds to a capillary diameter of about 0·4 mm. as in coarse systems. From this Casagrande concludes that in clays water flows in the fissures and cranks rather than through the fine capillaries.

Electroosmosis in relation to density, shrinkage and bearing strength.

The density and bearing strength of soils increase on electroosmosis. Shrinkage is the result of removal of nonfree water from the colloidal clay. In a particular experiment (17) by applying for some time 300-500 volts and 8-14 amps to a clay containing 80 per cent. water, the clay became hard enough to withstand a 22 lb. pressure on a 1 sq. cm. rod. The sample did not disintegrate or swell on being immersed in water for several months. Soil stabilized electroosmotically and electrochemically by employing aluminium anode and copper cathode was immersed in water for 2½ years without any visible sign of loosening.

APPLICATIONS

Electrical drainage was used on the field scale in several engineering operations in Germany and Norway during the second World War. The results of the few large scale applications of electrical drainage definitely indicate that it is an effective method of stabilizing the soil by drainage when no other method is practicable. Electrical drainage has been successfully applied to excavations in soft soils, and control of slips in earth slopes, on the field scale.

Soil hardening by electrical drainage can be studied under two classes, electroosmotic and electrochemical. The former deals with the consolidation and the consequential hardening of the moist soil by the removal of free water and sometimes even the combined water held by clay. This type of hardening is purely physical.

The latter type of hardening is chemical in nature, and is the result of electrolysis of dissolved salts. It consists in the exchange of sodium ions of clay by aluminium or iron ions. Such a base exchange involving change in the nature of clay is followed by aggregation and hardening. Both electroosmotic and the electrochemical methods of hardening have been studied and applied in practice. Three typical cases of large scale applications of electrical drainage are now described.

Salzgitter Railway cutting

During World War II, a cutting of water-logged soil had to be carried out near Salzgitter in Germany. (4, 12, 14). The location of this cutting was decided by mining considerations and the depth of the cutting by level of existing roads which crossed it. The cutting was for a double track railway and was about 1¼ miles long and 20 feet deep. The soil profile consisted of

4 feet of sandy soil on top and soft silt beneath. Normally no excavator could work owing to earth slips. Water table lowering by unaided drainage was not possible owing to the silty nature of the soil. Electrical drainage was adopted. Two lines of well points were sunk to a depth of about 25 feet on either side of the proposed cutting. Spacing between the well points being about 33 feet. A line of one inch diameter gas tubing was sunk between the well points to the same depth to act as anode. A length of 330 feet of cutting was stabilized at a time. The well point consisted of a perforated gas pipe and was surrounded by a layer of gravel and sand in order to avoid the clogging of the well.

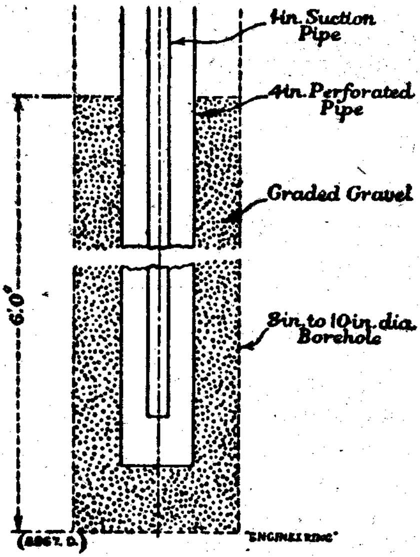

Figure 5—The well point

90 volts and about 25 amps, were applied to each well point. The water that collected in the well points which formed the cathodes was pumped out. The rate of flow by electrical drainage was increased to 150 times to the normal drainage. The scheme was reported to have functioned well. The moisture content was reduced from 20-24 to 14-17 per cent. and the excavation was made easy. A cross section of the Salzgitter cutting is shown in Figure 6.

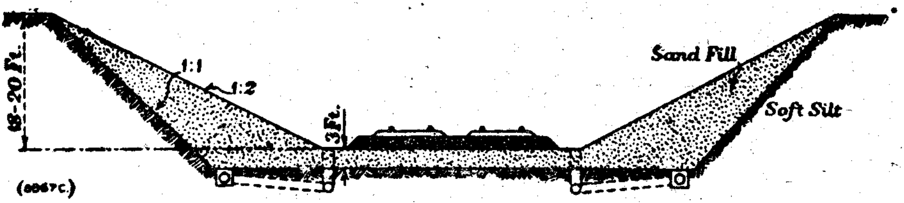

Fig. 6—Cross-section of salzgitter cutting.

U-boat pens construction

At Trondhjem, in Norway, during the second World War, excavation of an area of 550 ft. by 350 ft. and depth of 40 feet near the sea shore was carried out for use as U-boat shelter (4, 12, 14). The soil consisted of soft silt. Sheet piling suffered buckling and the silt flowed as fast as it could be removed by the traditional methods. Electrical drainage was intended to produce a stable belt of soil around the whole perimeter of the site. An inner and outer ring of sheet piling were driven around the entire site and a double row of well points was sunk between these rings. The two rows were about 45 feet apart and in each row the well points were placed at 30 feet intervals with $1\frac{1}{2}$ inch gas piping intermediate between them to serve as anodes. 40 volts and 20-30 amps. were applied to each well point. The flow of water was $\frac{1}{4}$ to 11 gallons per hour per well before and $2\frac{1}{2}$ to 105 gallons after the application of electrical drainage. The total flow of water was about 28,000 gallons per day. With this procedure the entire scheme of work was carried out satisfactorily.

Railway tunnel approach

As part of a projected railway line in the Larkendal valley near Trondhjem, a tunnel had to be driven partly through a rock and partly through clayey silt soil which was very soft having a moisture content of 18-37 per cent. The construction of an open cutting of a depth of about 60 feet in the soft soil was not practicable. Shield construction method which is the only possible method could not be adopted owing to limited time. The only possibility was to construct a tubular tunnel with an open cut with the help of electroosmosis, the cutting being filled in again after the completion of the project. The layout of the electrode system was similar to that of the railway cut near Salzgitter. The entire construction aided by electrical drainage was successfully carried out (4, 12).

In most of these cases of electrical drainage it is not always necessary to lower the moisture content of the soil to any appreciable degree. Even merely reversing the direction of flow of the seepage water by electric field will be sufficient to prevent earth slips and enable the excavator to work normally. In practice the electrodes are so arranged that the electroosmotic forces just oppose the hydraulic gradient and thus prevent the flow of water which is often the cause of instability during excavations. This method is effective although large quantities of water are not removed from the soil.

Increased drainage by electroosmosis

In the large scale electrical drainage investigations described above the magnitude of electroosmotic drainage is indicated in the following table I (17).

Table I

Drainage with Electroosmosis wells

	Depth ft.	Spacing in line	Gravity alone cu ft./day	Electroosmosis plus gravity cu. ft./day	Supply of electricity per well.	
					Volts	Amps
Railroad cut	25	33	0.7 avg.	105 avg.	90	25
U-boat pen	66	33	0·8-34	7·7-320	40	20—30
Tunnel approach ..	40	33	Negligible	3·3 avg.	30	15

Cost of electrical drainage

Though there have been number of instances of field investigations of electrical drainage, whether the process is economical or not has been a mooted question amongst the various investigators. The data on calculations of cost made by different authors are presented. The cost of electrical drainage in the Salzgitter railway cutting (14) was found to be 6*d.* per cubic yard of excavation and in the U-boat pens project 0·14*d.* per cubic yard. Russian workers have quoted the cost of various physical and chemical methods of soil stabilization and state that the electrochemical method is the cheapest (15). According to them the cost of electrochemical method is 10-50 roubles (1 rouble =50 cents) per cubic meter and that of chemical or mechanical method is 50-200 roubles. MacLean (11) states that the consumption of electricity is from 3-30 kilowatt hours per cubic yard.

Optimum particle size range for electrical drainage

Casagrande has given the particle size range of soils suitable for electrical drainage as shown in Figure 7 (12). The range is 0·4 m.m. to 0·004 mm.

Though soil is consolidated and hardened by electroosmosis, sometimes electrochemical action also comes into play depending upon the presence of dissolved silts in the soil and nature of the anode material. In presence of dissolved salts electrolytic action takes place and in the case of a reactive anode it reacts and goes into solution. If for instance there are iron and aluminium salts in solution base exchange takes place. Sodium and calcium clay will be converted into iron and aluminium clay. If the anode metal is either aluminium or iron, they corrode and go into solution during the passage of electric current. By base exchange the aluminium or iron clay will be formed. Aluminium and iron clays will be in the flocculated condition and develop greater rigidity and hardening. Thus electrochemical hardening is more pronounced than electroosmotic hardening. Electrochemical hardening is consequently of greater value in particular cases.

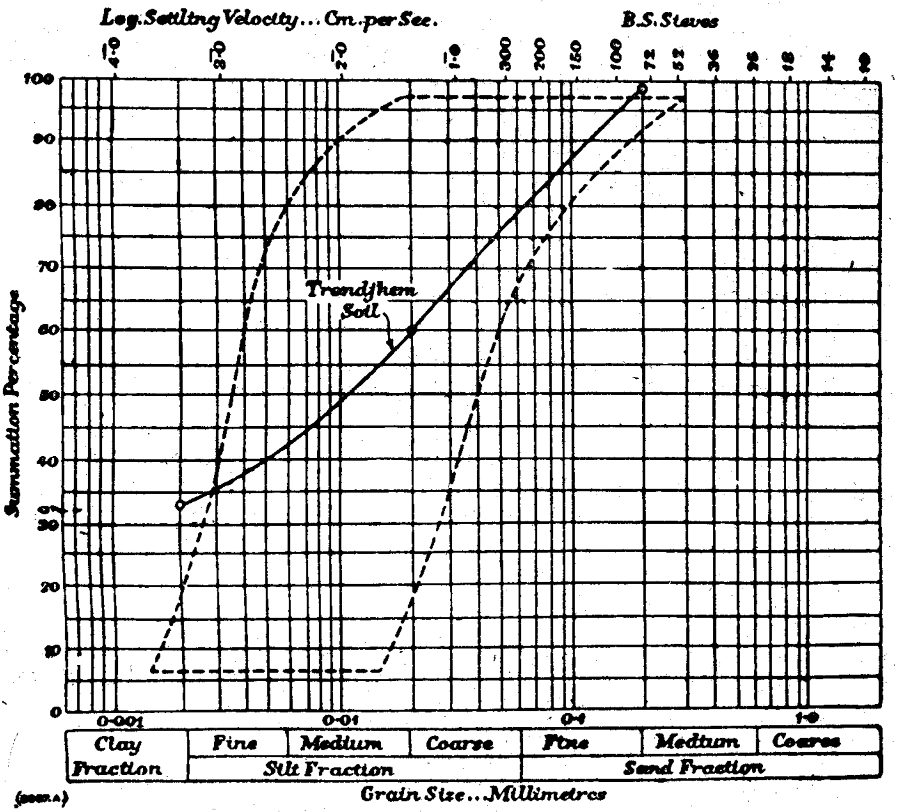

Fig. 7—Optimum particle size range of soils for electrical drainage.

In general electrochemical hardening can be promoted either by having aluminium and iron electrodes or by introducing soluble salts of these metals at the anode during electrolysis. Electrolysis is effected by impressing an external E.M.F. Casagrande has also suggested the possibility of utilizing the galvanic current (5, 6) produced in a couple of aluminium and copper electrodes. He has taken patents for electrochemical hardening by the two processes of introducing salt solutions at anode and of employing the galvanic current produced by aluminium, zinc, and magnesium anodes.

Consolidation around cathode and anode increases the bond between pile and the soil (1). Two timber piles 12 inch diameter with aluminium sheet cover were driven 20 ft. into soft plastic clay with skin friction of 250 lbs./sq. ft. After applying electric current through the two poles 6 ft. apart the skin friction of both the piles increased to 1250 lbs./sq. ft. Additional current decreased friction below peak value because of the development of shrinkage cracks near the electrodes. Electrodes pulled out an inch of soil attached to piles. White deposits were noticed on anode.

Certain physical properties like plasticity, shrinkage and swelling are minimized in several clayey soils following the passage of electric current and these changes are favoured by adding calcium chloride before treatment,

OTHER APPLICATIONS

The possibility of adopting the electroosmotic and the electrochemical methods of hardening soil in several other operations, has been suggested by various workers. It has already been used in a number of cases to deep excavations of unstable floating wet clays. Electrical drainage can be employed in stabilising foundations in clayey soils and removing excessive moisture from embankments (11). Its use in rapid cheap stabilization of bridge supports is suggested. Electrically stabilized clay forms a compact solid pedimant which prevents sinking of bridge supports into water logged clayey ground. Wooden bridge supports can be made into electrodes by attaching copper and aluminium plates.

The possibility of preventing frost heave (1) by the introduction of calcium chloride into the soil with porous anodes by passing electric current has also been tried.

Electrical drainage can be employed to dry out soil ahead in tunnelling and shaft sinking. Stabilization of soil beneath runways is also possible. The soft grounds under railway tracks and even under roads can be hardened by electrical drainage.

In all cases in which friction between metal and wet soil is involved, the frictional resistance can be reduced by the application of electricity which produces a lubricating film of water at the metal soil interface with metal as the cathode. Thus the tractive effort required on a scraper can be reduced. Similarly the draught on plough is reduced by about 5%.

It is possible to apply the principle of electroosmosis to reduce the tractive effort of a tank moving in a plastic soil. Thus there are many possible ways of using electricity in stabilizing soil and its practical application is limited to special projects where need is more important than cost. The range of applications is however to be broadened by laboratory and field investigations.

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